State Water Survey Division
ATMOSPHERIC SCIENCES SECTION
AT THE
UNIVERSITY OF ILLINOIS

Illinois Institute of
Natural
Resources

HYDROMETEOROLOGIC STUDIES ADDRESSING URBAN WATER RESOURCE PROBLEMS

by

S. A. Changnon, Jr., J. L. Vogel
F. A. Huff, and D. A. Brvnkow

FINAL REPORT

to

Division of Problem-Focused Research Applications
Directorate for Applied Science & Research Applications
National Science Foundation

Stanley A. Changnon, Jr.
Floyd A, Huff,
and
William C. Ackerman
Tr-incival Investigators

Grant Number:
NSF PFR78-05693

SEAL OF THE STATE OF ILLINOIS AUG. 26TH 1818

July 1980

TABLE OF CONTENTS

SECTION 1:

SECTION 2:

SECTION 3:

SECTION 4:

Page

SECTION 5:

SECTION 6:

SECTION 7:

SECTION 8:

APPENDIX A:

APPENDIX B:

LIST OF FIGURES

LIST OF TABLES

For this paper 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 system of units to the SI system.

Multiples for Converting from English to SI Units

	Length	
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)	0.02832	Cubic Meters (M^3)

ABSTRACT

This report summarizes the activities and results of a 1 1/2-year project which was part of a comprehensive 4-year hydrometeorological research program involving rainfall data collected in the Chicago Metropolitan Area. The major objectives were 1) to provide better methods of collecting and analyzing precipitation data for use in hydrologic design problems, so as to optimize design characteristics of urban sewer systems and other hydraulic structures; 2) to develop an operational rainfall prediction-monitoring system for the metropolitan area utilizing a combination of radar and raingage data; and 3) to transfer the research findings of objectives 1 and 2 to users. The project was performed with the close cooperation of city, state, and federal agencies, and private engineering firms.

The 1979 project involved an operational demonstration of a sophisticated weather radar system and a recording raingage network of 71 gages covering the urban region. The radar-rain monitoring system developed in this project was operated in a real-time demonstration mode for 2 months (18 June - 15 August) in support of the operations of the complex storm-sanitary sewer system of Chicago by the Metropolitan Sanitary District of Greater Chicago. The successful demonstration of this real-time rain measurement and prediction system indicated great potential for its use in the Chicago system and other major urban hydrologic systems in the nation attempting to manage and treat storm and sewer runoff. As part of this project, user guidelines have been developed for the design of radar and raingage systems elsewhere, a wealth of convective rainfall information useful in the design of hydrologic systems in Chicago and elsewhere has also been provided.

ACKNOWLEDGMENTS

The success of this research is the result of the direct contribution of many individuals who have been involved in the gathering of data, real-time operations, and data analysis. Neil G. Towery made many valuable suggestions during the development of the software for the prediction-monitoring rainfall systems, and assisted in the real-time operations during 1979. Herbert Yuen aided in the programming and development of the software package used for the prediction-monitoring system. Donald W. Staggs spent many hours maintaining and supervising the operation of the radar system. Eugene A. Mueller directed the engineering tasks and helped establish the communication link between the radar site and the Metropolitan Sanitary District. G. Douglas Green provided subsequent data analysis. Douglas M. A. Jones supervised the operation and data reduction of raingage data with the assistance of Phyllis M. Stone and Eberhard H. Brieschke. The graphics work was done under the supervision of John W. Brother, Jr. Julie K. Lewis, Rebecca A. Runge, Debbie K. Hayn and Sylvia H. Shepard typed the final report. In addition, the around-the-clock assistance of Stephen Ciesielski, Michael July, Paul Merzlock, Wilson Mulokwa, Marty Reynhout, and Brian Smith as radar operators was greatly appreciated.

The Metropolitan Sanitary District of Greater Chicago cooperated in every way possible and encouraged the continuation of this work, thereby contributing greatly to the success of this project. We also appreciate the cooperation received from the Northwestern Illinois Planning Commission, Chicago Department of Public Works, and the Cook County Forest Preserve District.

This material is based upon research supported by the National Science Foundation under Grant #PFR78-05693. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

SECTION 1

INTRODUCTION

This report summarizes findings from a 1 1/2-year operational and research project that served as the final effort in a 4-year program concerning hydrometeorologic studies which addressed three major urban water resources needs. These needs include better real-time information on heavy rainfall approaching and occurring over a water resources management system, better rainfall data for design of urban water structures, and rain data for water quality models.

Specifically, this project was the final phase of a 4-year research project, involving extensive field operational efforts, analyses, and summarization of the results. It was labeled the Chicago Hydrometeorological Area Project (CHAP). The project was funded by NSF/RANN (~70%) and State of Illinois (~30%) for the initial 24-month period, beginning on 1 February 1976. All the milestones established for the first two years were successfully completed. After an 8-month period of no NSF funding, the final 18 months (September 1978 - February 1980) was funded by NSF and the State of Illinois. The operations, data collection, and research of the first 2 1/2 years were geared to culminate in the final effort, which involved, as the primary task, a major real-time operational period to demonstrate the radar-rainfall systems utility in the operation of a large urban water resource system.

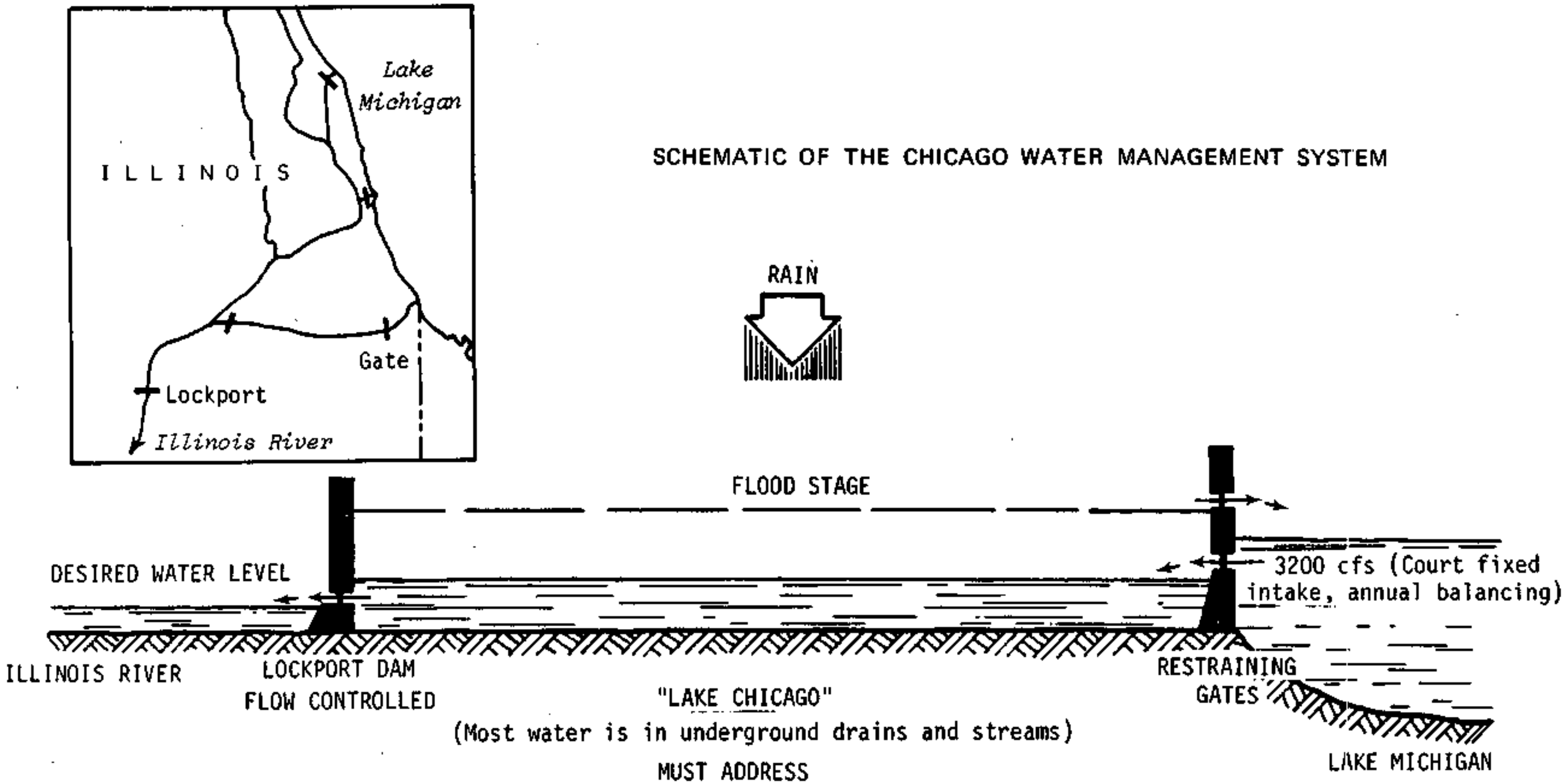
Chicago was selected as a study site because of its complex water system which must provide 4,600,000 people with fresh water for domestic and industrial uses (Pavia, 1979); maintain water levels for a major shipping canal; operate a combined storm and sanitary sewer system; and provide water storage to prevent flooding (Fig. 1). The flow from the Chicago River was diverted away from Lake Michigan to the Illinois River using a system of locks, including a dam at Lockport where the outflow is controlled for the total water system. Additional controls are being provided by a tunnel system (TARP) to store rainwater, which is the first phase of a comprehensive system to store storm and sanitary sewer flows for later treatment. The real-time management of this complex water system is further complicated by a control on the usage of waters from Lake Michigan imposed by the U.S. Supreme Court (1967).

The major CHAP objectives were to:

1) develop and demonstrate to the engineering user community a real-time, prediction-monitoring system for heavy storm rainfall utilizing a combination of modern weather radar and limited raingage data in the operation of the Chicago water resources system, with the ultimate goal of designing raingage and radar systems having widespread general application to other urban areas;

2) establish those precipitation measurements required in urban areas for optimizing design of urban hydrologic systems (storm and sanitary);

Figure 1. Overview of the Chicago Water Management System.



CONCERNS

- Water for transportation
- Water quality
- Flooding

MUST ADDRESS

- Illinois River needs for transportation
- Water uses in city and industry
- Maintenance of water quality standards
- Storage to prevent floods

CONCERNS

- Backflow of polluted floodwaters
- Excessive diversion

3) establish methods and techniques that make the Chicago-centered findings transferable to other cities facing similar problems of storm water and sewage disposal control; and,

4) provide precipitation data and information needed to define more accurately the time-space distribution characteristics of heavy storms in the Chicago region.

CHAP embraced two phases of interrelated research. One phase involved development of meteorologically-focused predictive and monitoring capabilities for rainfall over a large urban area. This invovled real-time operational techniques for the control and operation of urban hydrologic networks used to regulate the disposal of flood waters and to maintain acceptable water quality. In achieving this goal, the most advanced rain measurement system (including a new weather radar system and a raingage network) were employed, along with improved meteorological prediction schemes, realistic precipitation models, and current computer technology.

The second phase centered on studies of rainfall distribution characteristics using raingage data. The results have two major applications including 1) providing detailed information on rainfall distribution characteristics in the Chicago region, and 2) ascertaining those rainfall properties essential to optimizing storm sewer design and water quality modeling both in Chicago and in other large urban areas.

These phases required three major activities. First was a large-scale field program for collecting data and information essential to both major phases, and for performing a demonstration operation of the radar-raingage system to prove its utility to the potential engineering community. A comprehensive research program, the second activity area, utilized these field data in developing the necessary methods and techniques for accomplishing the various objectives. The third major activity area involved transmission of the results to users in Chicago and other major urban areas in a form particularly applicable to the user needs.

Operations and Research. The detailed precipitation measurements required for this 1 1/2-year project (and the preceding 2 1/2-years) have involved two basic types of information. These were a network of 317 recording raingages over 4,5000 mi^2 and a sophisticated weather radar system to provide the capability of accurately measuring precipitation. Operations of the raingage network was initiated on 1 June 1976, four months after funding became effective (2 months ahead of schedule). The radar system went into routine operation on 15 July 1976 with 3 months of operations in 1976 and 4 1/2 months in 1977. Modeling and computer interfacing required for later (1978) phases of the research were initiated in 1976. The raingage network has been in continuous operation since its inception. All activities have met the work shedule established prior to initiation of the research, as shown on Fig. 2.

The first two of three desired radar operational periods were completed at the end of the first 24 months, as planned in 1976 (see Fig. 2). Rapid processing of the radar and raingage data from their joint operational periods in 1976 and 1977 allowed data integration and initial evaluation of the radar-raingage system for monitoring (precipitation measurements) and for short-term predictions (echo motion, size, intensity, etc.). These analyses and the

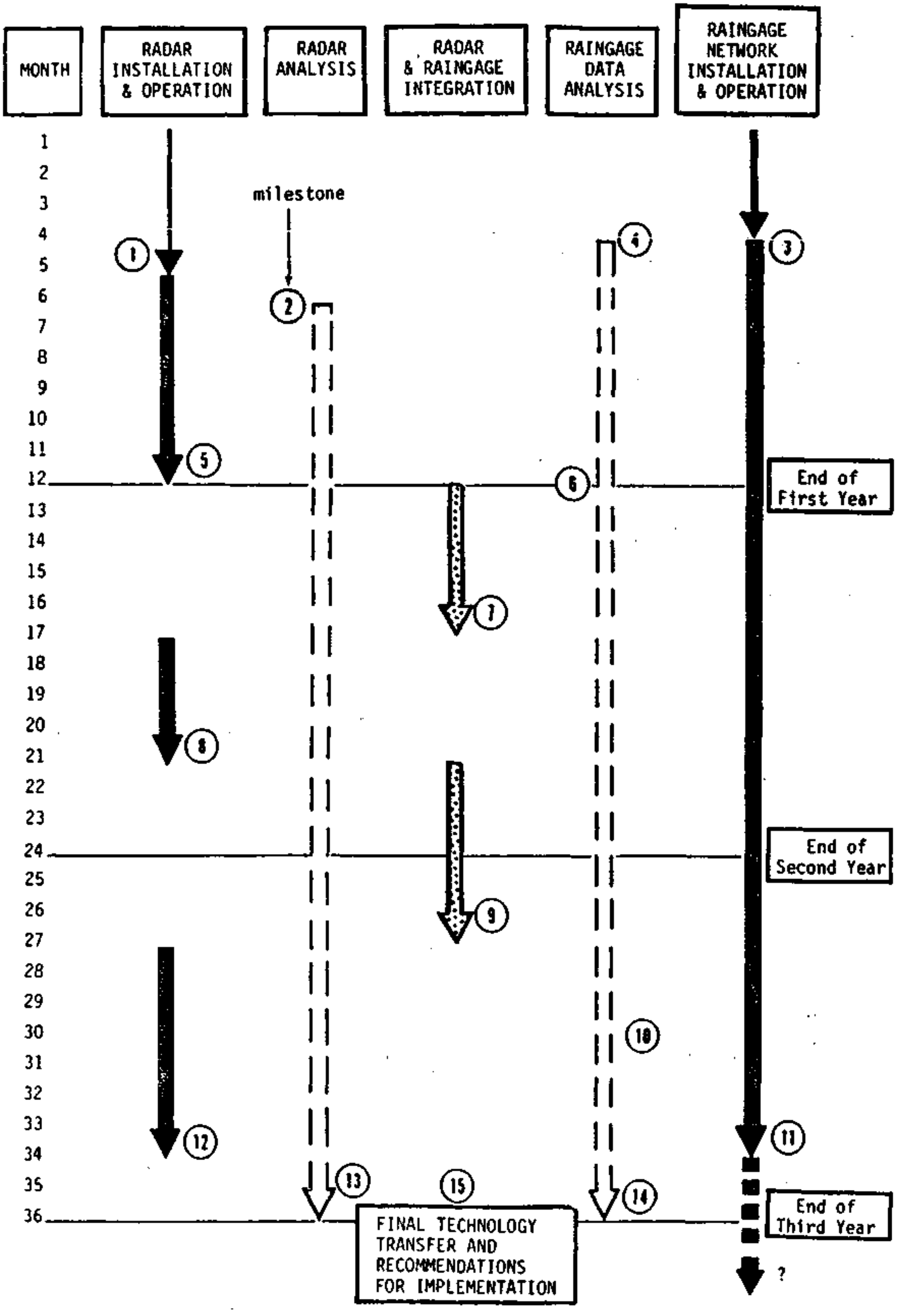


Figure 2. CHAP Milestones.

development of considerable allied software for the radar measurement of ongoing rain over the city were largely completed at the end of the 18th month (Milestone 7).

The data transmission system (radar data to MSD and MSD telemetered raingage data back to the radar) was completed in the 20th month. Beginning in the 21st month (from the start of the project in February 1976), a radar test operational period was initiated in cooperation with the Metropolitan Sanitary District (MSD). Its goal was the initial testing of the system for monitoring rainfall (both storm totals and rain during the last hour) over the metropolitan area, as developed from the radar-raingage integrated research. At the end of month 22 (Milestone 8) the short radar system test phase ended successfully.

The final period of integration and comparison of radar and raingage data was done in the last 18 months using the 1976, 1977, and 1978 data. Real-time procedures for the radar prediction of rainfall over the urban area were defined by March 1979 (Milestone 9). In June, July, and August 1979, a comprehensive radar operational phase was conducted with continuous, 24-hour, real-time data transmission to the MSD System Control Center in Chicago. This ended in mid-August 1979 (Milestone 12). A detailed manual for urban hydrologists described all facets of radar-raingage systems and their utilization in water resources systems has been prepared (Changnon et al., 1980).

During September-December 1979 the radar and rainfall analyses were completed with a focus on evaluating the results of the demonstration project (Milestones 13 and 14). Transfer of results has been extensive through direct interactions with users, the project advisory panel, talks at several scientific meetings, publications, and by conducting two user workshops in the summer of 1979 (Milestone 15).

Project Accomplishments. The major accomplishments of CHAP after 48 months of activity, fall within three categories: 1) the scientific, 2) the operational-technical, and 3) the user interaction areas.

Operational-Technical Achievements

1. Installation of a network of 317 recording raingages in the Chicago metropolitan region (world's largest network as shown on Fig. 3) and its continuous operation from June 1976 through September 1978, followed by operation of a 71-gage network (Fig. 4) to support the 1979 demonstration project (Huff and Changnon, 1977).

2. Installation of a complete weather radar facility (site found, buildings, erected, antenna pedestal foundation poured, and installation of radar system) by July 1976, at a site 40 miles SW of Chicago (Fig. 3).

3. Development of an automatic operational control system for the radar; interfacing of the radar with a computer system; the design and construction of special hardware needed for the operations; and, development of a communication system for transmitting routinely the computer processed radar data (and to receive telemetered raingage data) to the MSD Operational Center in downtown Chicago (Huff et al., 1978).

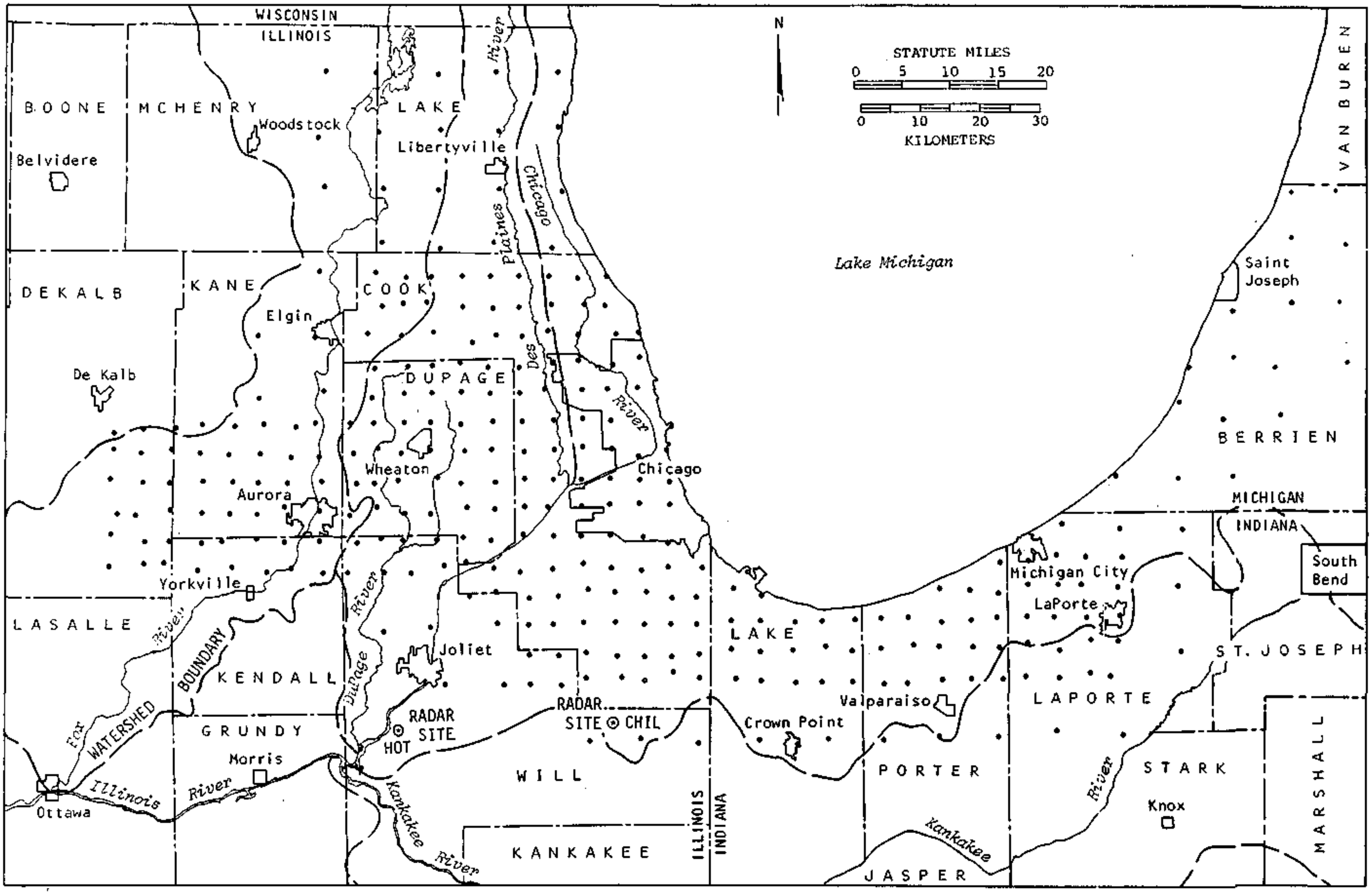


Figure 3. Study Area and Facilities for CHAP.

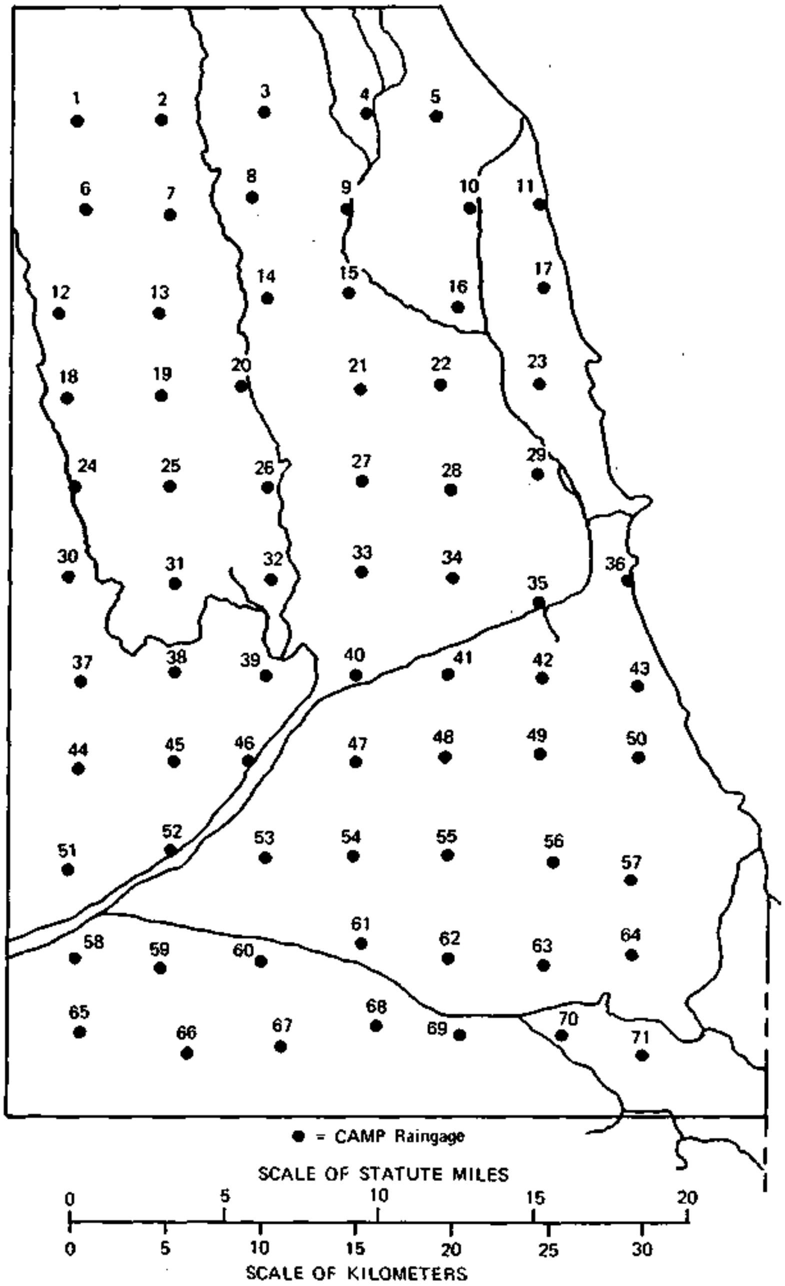


Figure 4. Raingage Network Summer 1979.

4. Operation of the radar for collection of all rainfall in the Chicago area in July-September 1976 and May-August 1977.

5. Operation of the radar on select rain dates in October-November 1977 to test the radar transmittal system and the radar-rain estimation technique in real-time for the MSD staff (Huff <u>et al</u>., 1978).

6. Operation of the radar computer and communication systems continuously from 18 June 1S7S to 15 August 1979, in a real-time demonstration program of the routine monitoring and prediction (every 30 minutes) of rainfall over the metropolitan area.

Scientific Achievements

1. Performed a radar-echo climatology for all past heavy rainstorms using all available historical data (Changnon and Huff, 1976).

2. Completed a climatic design study of heavy rain occurrences in the area over the past 25 years using available albeit limited historical raingage data (Huff and Vogel, 1976; Vogel, 1976; Vogel and Huff, 1977).

3. Made an in-depth hydrometeorological analyses of all excessive rainstorms in the CHAP network during 1976, 1977, and 1978 (Huff and Changnon, 1977; Huff and Towery, 1977; Changnon, 1978a).

4. Carried out extensive development of computer programs required for a) operation of the radar system, b) processing of the radar and raingage data, c) adjusting the radar signal with raingage data, and d) tracking motions of echoes and echo systems needed for the short-term prediction of rain over the urban area (Huff <u>et al</u>., 1978).

5. Made extensive analyses of radar-raingage relationships to define radar capabilities to measure rainfall (Towery and Huff, 1977; Hildebrand <u>et al</u>., 1979).

User Interaction Achievements

1. Establishment of a user-focused advisory panel of 8 persons from the private sector plus city, regional, and federal agencies; and a scientific, radar-focused, advisory panel of 3 persons. Both groups gave advice on the operational, research, and user activities (Changnon and Huff, 1976).

2. Publication of 14 papers in user journals and 5 reports aimed at the user audience (Changnon and Semonin, 1978).

3. Presentation of 25 professional papers at a variety of national and international conferences of the ASCE, AMS, AWWA, AGU, AND AWRA, and at 4 university-sponsored lectures (Changnon, 1978b).

4. Eight presentations on radio and/or TV to non-technical audiences.

5. A workshop of interested area scientists and engineers in Chicago in April 1977 (Changnon and Semonin, 1978).

6. Visits to engineering offices of 3 cities and to 2 regional urban planning agencies to discuss the project and their use of the data and final results.

7. Extensive requests for project data and results from many real and potential users promptly answered.

8. Distribution of several information letters and isohyetal maps of all 6 heavy rainstorms in 1976-1978 to 75 users in the Chicago region, each within 2 weeks after each storm event, plus annual rain summaries to all 230 people with a project raingage on their property.

9. Two user workshops conducted at the Joliet HOT radar site during August 1979, one for Chicago area leaders and the other for engineers and hydrologists from 18 cities across the nation.

10. Preparation of a user-oriented report presenting detailed guidelines for radar and raingage systems in cities.

This final report contains seven major sections, in addition to this introduction. The next section describes the rainfall monitoring and predicting methods used. This is followed by a description of the operational system and a case study from the 1979 demonstration project. The next three sections deal with the statistical evaluations of the rainfall monitoring and forecasting in the demonstration project. Then a section describes the user interactions including the publications, talks, and workshops concerning the project. Finally, a summary and recommendations section is presented.

SECTION 2

RADAR RAINFALL MONITORING AND FORECASTING

Radar has been used extensively as a research and an observation tool by meteorologists since the late 1940s. The real-time application of radar was limited to the determination of the direction, range, motion, and qualitative estimates of the precipitation intensity of radar echoes (storm elements). These measurements supplemented spatially and temporally the synoptic-scale observational networks and provided warning capabilities for various severe weather events. Detailed studies of echo characteristics were usually limited to research efforts after the event. It was recognized that quantitative measures of precipitation were possible, providing that relations between the echoes and precipitation rate could be obtained (Wexler, 1947; Marshall and Palmer, 1948; Byers et al., 1948). A brief review follows of attempts to adjust radar-indicated rainfall using the reflectivity factor and rainfall rates measured at selected raingages. For comprehensive review of the various methods to quantify rainfall measurements the reader is referred to Wilson and Brandes (1979).

Many researchers sought a relation between the reflectivity factor (Z)—a value proportional to the backscattered power measured by radar—and the rainfall rate (R). Such relations are often referred to an Z-R relations and are expressed in the form

$$Z = aR^b$$

where a and b are constants. One of the first relations obtained was that of Marshall and Palmer's (1948), which was

$$Z = 200R^{1.6}.$$

Using this relation Huff et al. (1956) tried to measure rainfall quantitatively, but they found differences in the Z-R relation under varying rain situations. They also determined that 3-cm radar, because of its attentuation, was unsuitable for the quantitative measurment of rainfall. A number of Z-R relations have been found for various locations, with different synoptic weather conditions, and for different precipitation types (Jones, 1956; Wexler, 1948; Atlas, 1964; Stout and Mueller, 1968). However, no single Z-R relation has been found whch can estimate effectively precipitation amounts from storm to storm or within storms at a single location (Brandes, 1975; Harrold et al., 1974; Huff, 1967; Wilson, 1970). Thus, adjustment of the radar-indicated rainfall must be made for each storm. For the real-time application of a radar-rainfall system measurements, adjustments must be made to the radar-indicated rainfall as the storm progresses. These adjustments require that either the Z-R relation must be changed for each storm or the Z-R relation be kept fixed and raingages used to adjust the radar estimates of rainfall. Only limited success has been obtained by changing the Z-R relation according to rain type or synoptic weather type (Atlas, 1964). However, some success has been obtained by adjusting the radar-indicated rainfall by raingages.

Wilson (1970) calibrated a WSR-57 radar in Oklahoma by determining a single calibration factor for observed convective rainfall at several gages. He found the accuracy of the areal rainfall measurements was improved. However, as the distance from the raingage increased the accuracy of the calibration constant decreased. Similar findings were reported by Woodley and Herndon (1970) and Zawadzki (1975). When Wilson (1976) compared the radar-measured rainfall to a dense raingage network he obtained an average error of 28% for his 1970 experiment.

Harrold et al. (1974) used a raingage near the center of the hilly sub-basins of the River Dee in North Wales (400 mi^2) to adjust radar measurements of steady rains, generally during the cold season. They applied the Marshall-Palmer Z-R relation and adjusted the constant A based on rain measurements. The radar-measured rainfall was in error by an average of 38% if no calibration gage was used, but the average error was reduced to only 14% when a single calibration gage was located near the center of the basin.

Woodley et al. (1975) used another method to determine the radar-measured rainfall from convective clouds over Florida. They obtained the average rainfall for five clusters of raingages and the corresponding average radar-measured rainfall over the same area. The radar return was adjusted by obtaining a gage to radar ratio and uniformly applying this weighted average to the radar-indicated rainfall. A modified Z-R relation for Miami originally developed by Sims (1970) was used. The constant A was varied to determine the true Z-R relation for each storm. The average error according to Wilson (1976) was approximately 20%.

Brandes (1974 and 1975) generated a field of calibration factors to overcome the problem of large variability within storms and measured convective rainfall over central Oklahoma. Once again the adjustment to the Z-R equation was accomplished by changing the constant A. With this technique, Brandes was able to reduce the average error of radar-measured convective rainfall to 14% using gages approximately 18 mi apart to adjust the radar-indicated rainfall.

Cain and Smith (1976, 1977) developed a sequential analysis technique for use with real-time raingage and radar data in adjusting radar-indicated rainfall estimates. The technique does not react to random, inherent variability of short duration that frequently occurs when comparisons are made between radar-indicated and raingage-indicated rainfall. The technique requires constant monitoring of the radar and raingage estimates of rainfall. Sequential tests are performed on the data and the radar estimates are adjusted only when systematic errors are indicated by the test. However, the operational time required for the technique to reach a decision on whether the radar-rainfall estimates are acceptable or need adjustment appears to be too long for the real-time monitoring and forecasting of rainfall over urban regions.

As indicated previously, a primary goal of the CHAP project was to develop techniques to predict and monitor convective rainfall. Such rainfall is highly variable both spatially and temporally within a storm and from storm to storm. Consequently, one Z-R relation cannot be expected to produce adequate quantitative information about the rainfall. Most previous adjustments of radar-rainfall (Woodley et al., 1974; Brandes, 1975) related total storm rainfall to the radar return after the storm event. For real-time monitoring and predicting of quantitative rainfall amounts the radar amounts must be adjusted continuously.

Several gage-radar adjustments procedures were considered. These included those employed by Woodley et al. (1975), Cain and Smith (1976), and Brandes (1975). For the real-time demonstration, the Brandes method was chosen because it was readily amenable to real-time use, could be programmed on the available on-site computer (TI-980), and could be used with the already available telemetered raingages.

Radar Characteristics

During the initial phase of CHAP (1976-1978), it was necessary to gather radar data coincident with rainfall data from the large dense raingage network in northeastern Illinois for developing and testing the various methods to be used in real-time monitoring and forecasting of quantitative rainfall amounts. The primary radar used during this phase of CHAP was the HOT (Hydrometeorological Operational Tool) radar, which was located at the Joliet field site (Fig. 3). However, it was not possible to have this radar operational by the summer of 1976 for data-gathering purposes. Thus, the CHILL (University of Chicago and Illinois State Water Survey) radar situated at Governor's State University (Fig. 3) was used during the summer of 1976. After the first summer of operations the HOT radar was used exclusively for data gathering and for the demonstration project during the summer of 1979. A description of each of these radars follows.

HOT Radar System — The HOT radar system consists of a FPS-18, 10-cm radar equipped with a digital processor and a minicomputer; a telemetry link between the radar operations center and MSD; and, rainfall data from 21 telemetered MSD raingages stored by a micro-processor at MSD headquarters and collected by the minicomputer twice each hour. The HOT radar was modified to operate at a lower PRF (Pulse Repetetion Frequency), and is able to operate at a range of 140 mi. A 20 ft parabolic mesh disk antenna was fitted to the radar giving a 1.5° beam width. Other details about the HOT radar are given in Table 1.

An incoherent digital processor containing 1024 range bins spaced 1.5 μs apart was built in-house for the HOT radar. This processor digitized radar echoes in 1024 range bins, averaged the radar signal, and archived radar data above the threshold on magnetic tape. Also, the digital processor transferred integrated data to the minicomputer. Table 2 provides other details about the HOT digital processor. To accommodate CHAP on-site data processing and data managing, the TI-980 computer memory was expanded to 28,672 words and a one million word disc memory and controller was added. A surplus high-speed line printer was acquired and interfaced to the system. Two modems and a hard copy terminal (Digital Equipment Corporation LA36) were purchased for use in displaying results at a remote location (MSD).

Hardware and software were developed to allow the radar data to be analyzed by the on-site computer. A high-speed interface was designed, constructed, and installed in the computer. This permitted the radar processor data to be dumped into the computer memory independent of the other computer activity. The processor dumps data every 96 milliseconds. Each dump

Table 1. Characteristics of HOT and CHILL Radars.

Peak	HOT	CHILL
Transmitter Power	600 Kw	600 Kw
Pulse Width (μs)	1	1
Pulse Repetition Frequency (Hz)	650	974
Antenna Diameter (ft)	20	28
Antenna Gain (db)	39.7	43.0
Beam Width (degrees)	1.5	1.0
Minimum Discernible Signal (A scope, dbm)	-103	-103

Table 2. Characteristics of Incoherent Data Processors.

	HOT	CHILL
Number integration channels	1	4
Number of range class per channel	1024	1024
Integration type	Block	Block or Exponential
Integration time constant	1 ms-ls	4 ms-32s
Range averaging	0	1-64 ms
Dynamic range of input	70 db	70 db
Analog to digital converter length (bits)	8	8
Value of least significant bit (db)	3/8	3/8

provides 1024 8-bit bytes at the rate of 750,000 bytes per second. This interface provides the option of averaging 2, 4, and 8 range bins together to reduce the total number of bins transfered to the computer. The interface generally puts one byte per 16-bit computer word; however, it may optionally pack two bytes per 16-bit word and thereby transfer all 1024 of the range bins. A software driver routine was written to connect this interface with the existing operating system. This allows the radar video to be accessed by application programs, just as the tape drives or any other input/output device is accessed.

Prior to the CHAP project the main function of the TI-980 was as an antenna controller and data handler. Thus, it was necessary to provide another device to handle the arithmetic and logical operations involved in controlling the antenna. A micro-computer was built which interfaced the TI-980 with the antenna functions. This micro-computer took over the burden of controlling the antenna and allowed the TI-980 to access significant variables such as current antenna position, scan program status, and time of day.

A second micro-computer system was designed, constructed, and installed for use at MSD. It monitored the MSD telemetered raingages and river level gages. The daily total for each of the 21 raingages plus as 5-minute and hourly averages for the 15 river level gages was calculated. This micro-computer was interrogated by the TI-980 at Joliet via dial-up telephone lines. As a service to MSD, it may also be interrogated by MSD's computer. Also installed at MSD was a 30-characters-per-second printer which allowed the TI-980 to print rainfall information while interrogating the micro-computer.

CHILL Radar System — The CHILL system is two radars of different wavelengths (10 cm and 3 cm) integrated into a single system. The 10-cm radar is built around an unmodified FPS-18 transmitter, and is fitted with a 28 ft antenna. More details about the CHILL's characteristics are given in Table 1. The data processing equipment is a special purpose processor which was built by Control Data Corporation to specifications. This processor provides the necessary time domain integration for both the 10-cm and 3-cm signals. The integration is normally performed with rectangular time windows (block integration). For the CHAP project the 3-cm wavelength radar was not used because the signal from this wavelength is highly attenuated and would provide poor measurement of radar-rainfall amounts. The information gathered at this wavelength is more relevant to cloud physics work.

The processor has a Doppler transform processor which provides 16,384 spectral coefficients for each 1/2 second of operation. These may be divided into either 32 ranges with 512-point spectra or in any combination of two satisfying the total data rate; e.g., 128 ranges with 128-point spectra.

The major deficiency of the CHILL system for use in CHAP is its relatively high pulse repetition frequency (PRF) which provides good velocity capability for Doppler representation, but the unambiguous range is only 86 mi. This range is not sufficient for monitoring rain systems as they move toward the Chicago region.

Adjustment of Radar-Indicated Rainfall

A large part of the early radar research in the CHAP project was devoted to processing and analysing radar and rainfall data collected during the summers of 1976 and 1977. These data were used to develop and test techniques for use in the real-time evaluation of radar-indicated rainfall. Most of these tests were performed using data collected during four 1976 storms by the CHILL radar and eight 1977 storms by the HOT radar. This summary focuses on the results which pertain to the Brandes method and the method of averaging employed in the real-time analysis.

For the analysis procedure, the radar data were read from raw radar tapes and a cartesian grid that covered most of the dense raingage network (Fig. 3) was produced. The southwest corner of the grid was located 28 mi west and 38 mi south of HOT. The spacing between grid points was 1.5 mi and the total grid coverage was 96 x 96 mi. The equivalent rainfall rates from all the range bins falling within a 1.5 x 1.5 mile square, centered at the grid points, were combined in an unweighted average to obtain the radar-estimated rainfall rate at a grid point through use of the CHAP Z-R relation ($Z = 300 R^{1.35}$). This produced a radar grid field of rainfall over the raingage field. The gage amount and radar amount were combined by averaging the radar value from the four closest grid points to a gage to obtain a radar-estimated rainfall amount at the gage. The rainfall measured by the raingage (G) was then divided by the radar amount (R) to obtain a G/R ratio. G/R correction factors were calculated for gage amounts greater than 0.01 in per time period.

The decision to combine the gage and radar amounts in this manner came only after an exhaustive analysis to determine the best method of obtaining R at a gage location. This included examination of: 1) the distribution of Z about selected grid points; and, 2) the distribution of G/R ratios using several methods of calculating G/R. It was found that the distribution of Z about grid points was quite noisy. For example, for one 15-minute period the Zs about a grid point ranged from 25 to 55 dbZ. The G/R distributions were also very noisy with the magnitude depending upon the rainfall rate, the number of grid points used for R, and the period of time over which the data was averaged.

The important point here is that the method of combining the two data sets was not arrived at lightly. The highly variable nature of Z in space and time meant that a relatively long (30 minutes) averaging period was needed and the data had to be smoothed over a relatively large (9 mi^2) area. The time and space resolution must be much finer than that generally used by other researchers because the rainfall results are to be used in a real-time prediction and monitoring application, as opposed to a post hoc evaluation of rainfall.

Radar Adjustment

The first step in the adjustment procedure was to obtain a G/R ratio at each raingage location. To avoid spurious values often associated with light rainfalls, several thresholds were applied. For instance, the raingage-indicated rainfall had to be greater than 0.01 in for a given time period (30 to 60 minutes) for a G/R ratio to be calculated and the radar-indicated rainfall at a grid point had to be greater than 0.01 in/hour. Additional, G/R ratios greater than 10 or less than 0.10 were considered spurious and omitted from the calculations.

Secondly, the radar-indicated rainfall value at each grid point was adjusted by multiplying it by a weighted average of all the G/R's within a specified distance of the grid point. The Brandes techniques uses a weighting factor developed by Barnes (1964):

$$e^{-r^2/EP}$$

where r is the distance from the gage to the grid point and EP is a variable weighting function. The variable weighting functions (EP) acts as an additional weighting control exerted by a G/R at a distance grid point. Small values of EP concentrate most of the weight to close gages (G/R's) and large values allow gages (G/R's) farther away to carry more weight.

Analyses with a gage density of 1 per 9 and 18 mi^2 used a weighted average of all G/R's within a 8 mi radius and an EP of 9. In analyses of gage densities of 1 per 36 and 54 mi^2 a weighted average of all G/R's within a 10 mi radius and an EP of 20 were used. Again, the values selected for the gage-to-grid point distances and EP were decided upon after extensive background analyses on the effects caused by changing these values, consideration of the grid and gage spacing, and the size of convective rain entities.

The assessment of the accuracy of the radar-indicated rainfall has been determined in two ways. Most investigators have used a dense raingage network to determine the accuracy and veracity of the radar-indicated rainfall measurements (Woodley et al., 1975; Brandes, 1975; Wilson, 1976; Hildebrand et al., 1979). For the Dee Weather Radar Project in England, Harrold et al. (1974) used the radar-adjusted rainfall field as the best estimate attainable for rainfall features smaller than those measured by the raingage field. For our comparison, the areal mean rainfall from the large, dense raingage network was used as a standard of comparison.

The areal mean rainfall and percent errors from three data sets (unadjusted radar rainfall, gages alone, and adjusted radar rainfall) were calculated. The areal mean rainfall from the full density network (one gage every 9 mi^2) was the standard with which all other estimates were compared. The full density network was divided into 5 sub-areas ranging in size from 300 to 600 mi^2. Areal means were computed for each area, and the percent absolute error was calculated by subtracting the estimated rainfall from the full density gage rainfall and dividing by the full-density gage rainfall.

Mean areal rainfalls and the percent absolute errors from the three rainfall data sets were calculated for various raingage densities (full, 1/2, 1/4, 1/6, 1/9, and 1/12) and for various time periods (30 minutes, 60 minutes, and total storm) of averaging the data. The gage density was reduced to obtain information on gage density requirements for operation of a hydrologic system which would employ both radar and raingages in real time. The variation of time averaging periods was made to determine the optimal period over which the rain rate should be averaged for maximum accuracy.

Results f com the summer of 1976 and 1977 are presented separately in Tables 3 and 4 because different radars were used each summer, and these radars had different characteristics (Table 1). Tables 3 and 4 show the average percent error for the unadjusted radar, adjusted radar, and gage-only mean rainfall using the full-density raingage network (Fig. 3) as the standard of comparison for sampling times of 30 minutes, 60 minutes, and total storm rainfall. Only those periods when the mean areal gage rainfall was 0.1 in or more are given.

During the summer of 1976 the unadjusted radar-rainfall error ranged from 61 to 67% percent and the error decreased as the storms were integrated over longer times. The accuracy of the adjusted radar-rainfall measurements and the gage-only rainfall decreased as the density of the raingages decreased, as expected. However, the radar-adjusted rainfall measurements began to show improvement over raingage-measured rainfall amounts when the adjusted gage density was between 1/6 and 1/9 that of the dense raingage network, and the adjusted radar amounts were comparable to the gage-only rainfall amounts with a raingage density of one gage every 36 mi^2 or 1/4 maximum gage density. Only minor percent error differences were noted between the various sampling times.

During the summer of 1977, the unadjusted radar error ranged from 42 to 45%, with no trend toward smaller errors by integrating over smaller time periods. Generally, the radar-adjusted rainfall amounts, showed decreased accuracy as the density of the adjusting raingage network was reduced. The radar-adjusted rainfall measurements for 30 and 60 minute periods had errors comparable to the gage-only amounts at a raingage density of 1/6 or less. Comparisons between the radar-adjusted rainfall between 1976 and 1977 show that the percent error for the various raingage densities are similar.

There was some concern that the "artificial" area boundaries (division of the network in areas) might cause some erroneous results because only portions of a storm were sampled by the gages and radar. Many times there is a displacement in time and space between radar-indicated rainfall and gage-indicated rainfall caused by the winds blowing the rain in one direction or the other from near the base of the cloud (radar measurement) to the ground level (raingage measurement). Furthermore, other researchers results had been based on total storm (in time) and entire network averaging. Thus, the analysis was repeated using the entire network as an area.

The analysis for results for 1976 and 1977 is shown in Tables 5 and 6. Generally, this analysis showed that the percent error of the adjusted radar-rainfall values were less than those for partial areas. The adjusted radar-rainfall error for the whole area do compare favorably with other attempts to adjust radar-rainfall measurements (Wilson, 1976; Brandes, 1975; Woodley et al., 1975; Harold et al., 1974). However, the adjusted radar-rainfall percent error was usually greater than the comparable gage-only rain error.

Table 3. Comparison of absolute percent errors (X) of unadjusted radar rainfall, adjusted radar rainfall, and raingage only rainfall compared to the full-density network. (N) is the number of samples. Gage areal mean rainfalls ≥ 0.1 in. are included. Values are for 30 minute, 60 minutes, and total storm averaging for four storms in 1976.

Gage Density	AREA mi	Unadj Radar		Adj Radar		Gage Only	
		N	X	N	X	N	X
				30 Minute			
Full	9	19	67	19	10		0
1/2	18	19	67	19	12	19	4
1/4	36	19	67	19	18	19	16
1/6	54	19	67	19	19	19	15
1/9	81	19	67	19	26	19	33
1/12	108	19	67	19	26	19	37
				60 Minute			
Full	9	20	62	20	12		0
1/2	18	20	62	20	16	21	7
1/4	36	20	62	20	14	21	12
1/6	54	20	62	20	17	21	22
1/9	81	20	62	20	21	21	37
1/12	108	20	62	20	30	21	28
				Total Storm			
Full	9	10	61	10	11		0
1/2	18	10	61	10	11	10	6
1/4	36	10	61	10	12	10	6
1/6	54	10	61	10	12	10	13
1/9	81	10	61	10	22	10	33
1/12	108	10	61	10	26	10	19

Table 4. Comparison of absolute percent errors (X) of unadjusted radar rainfall, adjusted radar rainfall, and raingage only rainfall compared to the full-density network. (N) is the number of samples. Gage areal mean rainfalls ≥ 0.1 in. are included. Values are for 30 minute, 60 minutes, and total storm averaging for eight storms in 1977.

Gage Density	AREA mi	Unadj Radar N	Unadj Radar X	Adj Radar N	Adj Radar X	Gage Only N	Gage Only X
				30 Minute			
Full	9	59	45	59	11		0
1/2	18	59	45	59	14	59	5
1/4	36	59	45	59	17	59	9
1/6	54	59	45	59	22	59	17
1/9	81	59	45	59	19	59	17
1/12	108	59	45	59	23	59	28
				60 Minute			
Full	9	46	42	46	11		0
1/2	18	46	42	46	14	46	5
1/4	36	46	42	46	17	46	9
1/6	54	46	42	46	19	46	14
1/9	81	46	42	46	31	46	22
1/12	108	46	42	46	23	46	25
				Total Storm			
Full	9	34	45	34	10		0
1/2	18	34	45	34	11	34	5
1/4	36	34	45	34	15	34	7
1/6	54	34	45	34	19	34	14
1/9	81	34	45	34	27	34	17
1/12	108	34	45	34	21	34	17

Table 5. Comparison of absolute percent errors (X) of unadjusted radar rainfall, adjusted radar rainfall, and raingage only rainfall compared to the full-density network. (N) is the number of samples. Gage areal mean rainfalls ≥ 0.1 in. are included. Values are for 30 minute, 60 minutes, and total storm averaging for four storms in 1976 (full network).

	Gage Density AREA	Unadj Radar		Adj Radar		Gage Only	
	mi	N	X	N	X	N	X
				30 Minute			
Full	9	6	65	6	6		0
1/2	18	6	65	6	5	6	3
1/4	36	6	65	6	11	6	7
1/6	54	6	65	6	16	6	18
1/9	81	6	65	6	9	6	9
1/12	108	6	65	6	16	6	19
				60 Minute			
Full	9	5	63	5	11		0
1/2	18	5	63	5	10	5	2
1/4	36	5	63	5	15	5	15
1/6	54	5	63	5	19	5	15
1/9	81	5	63	5	14	5	12
1/12	108	5	63	5	18	5	10
				Total Storm			
Full	9	4	69	4	21		0
1/2	18	4	69	4	19	4	4
1/4	36	4	69	4	14	4	6
1/6	54	4	69	4	17	4	9
1/9	81	4	69	4	16	4	14
1/12	108	4	69	4	16	4	14

Table 6. Comparison of absolute percent errors (X) of unadjusted radar rainfall, adjusted radar rainfall, and raingage only rainfall compared to the full-density network. (N) is the number of samples. Gage areal mean rainfalls ≥ 0.1 in. are included. Values are for 30 minute, 60 minutes, and total storm averaging for eight storms in 1977 (full network).

Gage Density	AREA	Unadj Radar		Adj Radar		Gage Only	
	mi	N	X	N	X	N	X
				30 Minute			
Full	9	7	37	7	9		0
1/2	18	7	37	7	10	7	2
1/4	36	7	37	7	13	6	5
1/6	54	7	37	7	15	7	7
1/9	81	7	37	7	12	7	7
1/12	108	7	37	7	17	7	13
				60 Minute			
Full	9	13	42	13	8		0
1/2	18	13	42	13	9	13	2
1/4	36	13	42	13	10	13	6
1/6	54	13	42	13	13	13	7
1/9	81	13	42	13	16	13	10
1/12	108	13	42	13	17	13	14
				Total Storm			
Full	9	8	39	8	6		0
1/2	18	8	39	8	5	8	1
1/4	36	8	39	8	8	8	3
1/6	54	8	39	8	16	8	5
1/9	81	8	39	8	16	8	8
1/12	108	8	39	8	14	8	9

Results of Radar-Rainfall Adjustments

As found throughout the study, the least accurate measurements occurred with the unadjusted radar. The size of the adjusted radar and raingage errors was strongly dependent upon the raingage density. Our results further suggest that under real time operational conditions, when fine tuning of the radar-indicated rainfall is not feasible, an average error of estimate of approximately 20 percent is about the best that can be achieved. Frequently the error is much greater. This error is based upon 30-minute and 60-minute measurements of average rainfall intensity during 1976-1977 over areas ranging from 200 to 800 mi^2.

Results from the individual storms indicate that accuracy is best in medium to heavy rainfall rates and rains covering 70% or more of the area being monitored. The least dependable results were observed in light rain either widespread or with scattered centers.

Another important finding from our studies to date is that with an effective radar adjustment procedure, measurement accuracies for 30-minute amounts are approximately the same that others have found for total storm or daily rainfall. The relative spatial variability is normally greater within partial storm than in total storm periods. This results in greater sampling errors when measurements are required over short intervals, such as the 30-minute period used for the CHAP project. However, relatively accurate measurements of radar-indicated rainfall over short-time periods are essential for the effective operation of a real-time urban hydrologic system.

The radar-adjusted rainfalls provide considerably more detail about the structure of the rainfall than can be obtained by even the dense raingage network. Harrold *et al*. (1974) have argued that the best rainfall representation is given by the radar-adjusted rainfall field, since it fills in the needed detail between raingages. Indeed, when the adjusted radar-rainfall field is used as the standard of comparisons, the radar-adjusted rainfall field is better than the raingage-measured rainfall at all raingage densities. The radar has the added advantage of being able to provide measurements over a total area, showing the position of relative rainfall maximums and minimums. Thus, the radar provides information about the amount of rain falling between gages and over small subareas (basins) that cannot be provided by a raingage network.

The CHAP analyses has led to certain tentative conclusions and recommendations regarding criteria for quantitative estimates of rainfall intensity within operationally acceptable limits. For prediction purposes, it is essential to have quantitative estimates of rainfall intensity in storms before they reach the urban area. For this purpose, the average measurement error of radar-indicated rainfall should not exceed 30 percent which will be useful for predicting rainfall amounts expected over the urban area. These gages should be located within distances of approximately 20 mi in the directions from which most storms move. This would be from south through west to northwest in the Chicago region, and the average gage density for convective rainfall in the Midwest U.S.A. should be approximately one gage per 100 mi^2. For initial estimates of the rainfall beyond the telemetered gages, use should be made of a climatic-derived, Z-R equation for the region of interest. This equation should contain an average adjustment factor of the radar-observed rainfall field, based upon observed relationships between unadjusted radar and raingage measurements of rainfall.

Within the urban area, greater accuracy in the measurement of rainfall is needed than in the periphery region where the measurements are primarily for prediction purposes. Our studies indicate the telemetered raingage density should be increased to one gage every 25 to 50 mi^2, if possible, so as to keep the average measurement error at 20 percent or less. 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.

Evaluation of Echo Tracking Program

The component parts of a convective storm system often exhibit relatively large variability in velocity, intensity, and areal coverage which are properties that help determine the storm rainfall output over a given area. Thus, reliable predictions of quantitative storm rainfall amounts with radar requires real-time tracking and analysis of radar echoes as they approach and cross the region of interest. For the real-time tracking of radar activity it was decided to adopt an echo-tracking routine developed for the Flordia Area Cumulus Experiment (FACE) by Wiggert et al. (1976). This tracking program was designed as a bookkeeping tool to record objectively the location, areal size, rain rate, rain volume, and direction and speed of motion of individual radar echoes in sequential fields of digitized data for post analysis of storms. Tracking echoes with time required that merging, splitting, growth and decay processes be documented. This was accomplished by giving each echo one identification number and status classification. The possible status types included: new, result of a merger, result of a split, tracked, lost, lost because of merging and lost because of splitting.

The cell tracking method developed by Wiggert et al. (1976) isolates echoes above a defined threshold, describes echoes by fitting a bi-variate normal distribution, matches the present echoes to the last set of data, classifies each echo according to its status, and determines various physical parameters, such as size, volumes, position and others. Previous work with this tracking program (Simpson et al., 1978) indicated that it performed well using radar data taken at 5-minute intervals. The real-time operation of such a tracking scheme demanded that echo tracking be done at intervals greater than 5-minutes, usually at 10- or 15-minute intervals. This is usually dictated by computer availability in real-time. Consequently, an evaluation of the FACE echo-tracking program was made using 15-minute intervals.

Six Chicago storms were analyzed using the FACE tracking scheme. Echoes found in the instantaneous fields of digitized radar data were tracked between intervals of approximately 15 minutes. The echo classifications described above were assigned for each echo in each time interval. For analysis purposes, a merger was defined, as the consolidation of two or more previously separate echoes at the 0.2 in/hr isopleth of rain rate. The splitting of an echo into two or more components also occurred at a threshold of 0.2 in/hr. This rain rate criterion does not imply a time and rain intensity when separate echoes begin to physically interact. Since, as heavy rainfall, greater than 0.5 in/hr is the focal point of the Chicago study, 0.2 and 0.4 in/hr thresholds were considered. The 0.2 in/hr threshold was employed as it allowed the retention of the echo field pattern, whereas the 0.4 in/hr threshold reduced the continuity between consecutive radar scans. An area threshold of 24 mi^2 (6 grid points) was imposed, as well as the rain threshold to eliminate smaller, short-lived (< 15 minute) echoes.

The evaluation of the tracking program involved a visual comparison of the FACE digitized radar echo fields with the same fields traced from film records of the radar echo field. This was done to insure that the echoes from the radar film and the digitized radar images corresponded. Then, internal checks of the PACE program were made to determine whether the status decisions made by the program were comparable to those made by an individual.

The results from this analysis showed that the computer-derived tracks were correct 82% of the time. The major decision errors by the objective computer tracking system at this longer time interval (15 minutes) occurred when radar echoes were splitting and merging, which are often important processes affecting the production of rainfall. Many of the tracking errors made by the objective program could have been eliminated by shortening the interval between consecutive time frames. Echo fields change rapidly and propagation, new growth and decay are sometimes difficult to distinguish from translation, persistence, merging and splitting. Thus, it was concluded that tracking data taken at intervals of greater than 5 minutes using this program cannot be considered reliable in the Midwest, and if it is necessary to use data intervals greater than 5 minutes the tracking would most profitably be done by a combination of man and machine. For the real-time demonstration project it was not possible to track radar echoes at 5-minutes intervals using a program similar to that of Wiggert et al. (1976), because of minicomputer limitations. Thus, we concluded that for the real-time demonstration project a man-machine mix with a 10-minute interval for echo tracking would be used. The computer would isolate the echoes, keep track of bookkeeping, and make computations. The operator would match echoes from one 10-minute frame to the next.

Software Development

Prior to the demonstration project, software was developed for real-time use in the radar-rainfall system. The software was limited by the constraints of the minicomputer storage capacity, the digital processor capabilities, and the calculating power of the minicomputer. The software system was achieved through a mixture of man and machine. The computer made quantitative calculations and extrapolations, while the human operator contributed the intelligence required for pattern recognition and monitored the overall operation of the system.

The final system permitted several independent programs to operate concurrently. The execution of each program was scheduled for a specific time, or was suspended waiting for a signal from another program or from the operator before beginning or continuing. Programs not ready for execution were automatically moved onto disc memory to wait. These features allowed the software system to be divided into several modules to run as independent programs.

A flow chart showing the various modules and their interrelationships is given in Fig. 5. The most important modules were: 1) DATA COLLECTION, to generate cartesian grids; 2) CELL TRACKING, to isolate and trace individual echoes; 3) FORECAST, to extrapolate echo paths, 4) TOTAL, to monitor and maintain current rainfall totals; and 5) EDITOR, to interrogate the meteorologist and transmit the final products to MSD. These programs signaled each other via flags maintained by the operating system, and exchanged data via shared disc files. An example of how these modules functioned in real-time is given in a case study in the next section.

DATA COLLECTION. The DATA COLLECTION program took data from the video processor and generated cartesian grids used by the other analysis programs. The grid size was fixed at 64 by 64, with a grid spacing of 2 × 2 mi. This was equivalent to having a raingage every 2 miles over 16,384 mi^2. The grid origin was generally located at 76 mi west and 54 mi south of the radar site. The grid was situated so as to monitor storms coming from the west or south. However, the origin could be moved by the operator to monitor storms moving from the north or east.

The DATA COLLECTION program was scheduled to run every 5 minutes, and was assigned the highest priority. Thus, it took precedence over any other program ready for execution or being executed. The first task of the DATA COLLECTION program was to signal the antenna controller to begin the antenna scan sequence. The antenna controller was programmed to rotate 360° at 12°/second for each elevation angle. The first elevation scan angle was 0.7°. At the completion of each azimuth rotation the elevation angle was increased by 1.5° until the storms were topped. Although all of the elevation scans were archived on tape by the video processor, only the two low angle scans were used for real-time operations.

Once the antenna was in motion, the video processor produced a measurement of returned power every 100 milliseconds, or approximately every 1.2° of azimuth. The hardware interface, which connected the video processor to the computer, applied a range squared correction to the returned powers and deposited 512 reflectivity range bins in the computer memory. These reflectivities were converted to rainfall rate estimates by an evaluation of the equation: $R = 0.136Z^{0.74}$ mm/hr. Since the spatial resolution of the radar (0.5 km by 1.5°) considerably exceeded the output grid 2 × 2 mi, a simple average of rainfall rates from all range bins closest to each grid point was used to estimate the rainfall rate at each grid point. A separate rainfall rate grid was generated for both the 0.7° and 2.2° elevation scans. These were combined to form a composite grid to overcome some blockage of the 0.7° scan in the northwest, and ground clutter contamination at close ranges. Data at ranges up to 30 mi were selected from the 2.2° scan. At ranges beyond 30 mi, respective grid points from the 0.7° and 2.2° scans were compared and the more intense rainfall rate of the two scans was retained for the composite grid.

Every other time the DATA COLLECTION program ran (every 10 minutes), the composite grid was written to the NEW FRAME disc file. A signal was sent to the CELL TRACKING program to indicate that new data was available. Every time the DATA COLLECTION program ran (every 5 minutes), it added the composite grid

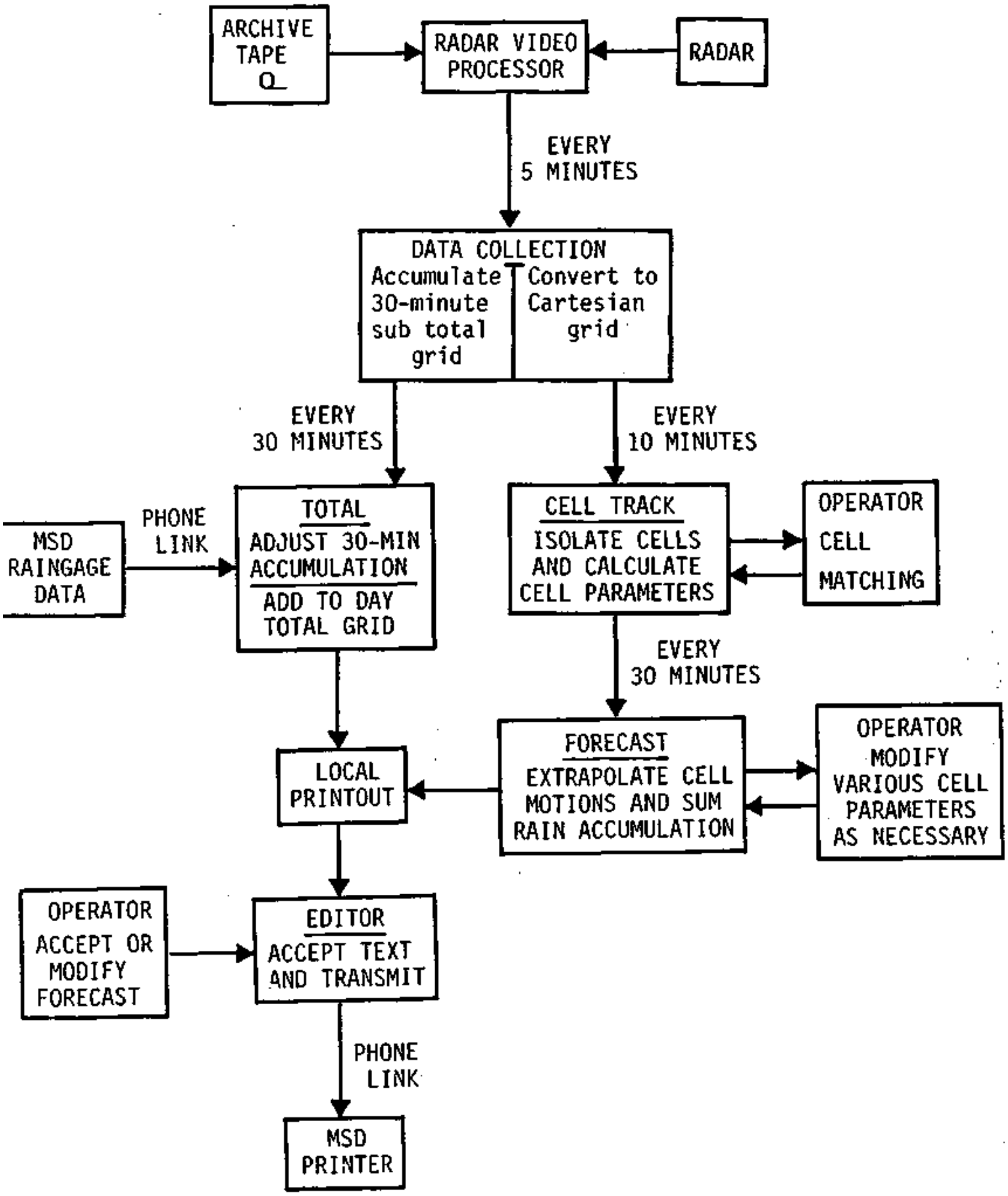


Figure 5. Software Flow Chart for CHAP Forecasting-Monitoring System.

to the SUBTOTAL grid which resided on a disc file. After 30 minutes of data accumulatd in the SUBTOTAL grid, the DATA COLLECTION program initiated the execution of the TOTAL program.

TOTAL. The grid containing the rainfall accumulation was stored in a disc file called DAILY TOTAL. The TOTAL program read the 30-minute rainfall accumulation (SUBTOTAL), modified it (optional) based on raingage information, and added it to the DAILY TOTAL grid. The modification of the radar-estimated rainfall was deemed advisable due to the uncertainty of the reflectivity-rainfall rate relationship caused by varying drop size distributions. The 30-minute amounts from the 22 telemetered raingages, the radar-indicated rainfall amounts at the gage locations, and the ratio of the gage/radar amounts were printed locally for the operator's use.

The optional adjustment routine was modeled after one described by Brandes (1975). It used a simplified Barnes (1964) objective analysis technique to estimate a gage/radar ratio at each grid point in an area limited by the coverage of the 22 MSD raingages. This ratio scaled the radar rainfall estimates to obtain better agreement with the gage amounts. During the 1979 operational period, this adjustment procedure was not used due to interface problems with some of the raingages. Toward the end of the operational period, the operator was able to adjust the rainfall amounts transmitted to MSD by a subjective evaluation of those gages which were reliable.

CELL TRACKING. Every 10 minutes, the CELL TRACKING program isolated individual cells on the instantaneous rain rate grid (NEW FRAME). A set of statistics was printed to inform the operator of the current area, average rain rate, growth trends, and storm velocities for each cell. The cell tracking program is a simplified version of the program developed by Wiggert et al. (1976), which was written in FORTRAN and made extensive use of floating point arithmetic and transcendental functions. This program was developed with Florida data on a 1.1 x 1.1 mi grid which was updated every five minutes. Computer limitations in CHAP called for a 2 x 2 mi grid updated every 10 minutes. Previous research indicated that such an interval between frames would have degraded the performance of the automatic cell tracking routine. This consideration, plus the relative difficulty of using floating point arithemtic on the TI-980 computer, led to the development of an interactive graphics routine requiring the operator to match echoes from the latest data scan (NEW FRAME) to echoes from the scan observed 10 minutes earlier (OLD FRAME). By replacing a considerable amount of artifical intelligence in the original program with a skilled operator, a program using only 16 and 32 bit fixed point numbers could be implemented.

FORECAST. The FORECAST program ran every 30 minutes. Forecasts for the north, central, and south MSD areas for the following 30, 60, and 120 minutes were made by extrapolating the centroid motion of each cell selected by the operator during cell matching. It was anticipated that the centroid motion and other measured parameters would occasionally contain obvious errors. For example, if the change in the size of the convective entity was 400% in the last 10 minutes, it is conceivable that this was a newly developed storm which, quite normally, grew explosively during the first minutes of its life. The application of such an areal change for every 10 minutes over the next 120 minutes would develop a huge cell which would be unrealistic and bias the forecast. At other times the computed motion of the convective entity might be faulty or the motion would not reflect the cell movement anticipated to occur over the region. Therefore, each cell was presented to the operator in the form of a full contour map along with its measured parameters and the operator had the option of modifying most of the information generated by the cell tracking program.

After all parameters were accepted by the operator the cell centroid was then moved in twelve 10-minute time steps. All grid points within the cell which passed over any of the target areas contributed to the forecast amount for that area. The three forecast amounts were saved after 3, 6, and 12 time steps to generate 30-, 60-, and 120-minute forecast subtotals.. During each time step, the apparent grid spacing was scaled in proportion to the square root of the areal rate of change to simulate areal growth or decay. This growth process was terminated if the cell area reached a limit set by the operator. Similarly, the rainfall intensity was allowed to change with each time step. After every third time step, the program drew the outline of the three target areas to indicate the relative motion and size of the target areas with respect to the cell.

This extrapolation process was repeated for every cell selected by the operator. The final forecast was the sum of the forecast subtotals from these cells, and was printed in hundredths of an inch additional rainfall accumulation.

EDITOR. The forecast EDITOR program printed the average rainfall accumulated in the three target areas as measured by the radar. The operator examined the radar estimated accumulations an the forecasts, altered the values, if necessary, and then entered the text of the message transmitted to MSD. The meteorologist made a subjective evaluation of the uncertainty of the situation. Taking this into consideration, he converted the numbers from the FORECAST program to a range of expected additional accumulations and the most likely total rain in the three forecast areas for the next 30, 60, and 120 minutes. The computer automatically dialed the terminal located at MSD and transmitted the message entered by the operator. A subset of the TOTAL rain accumulation grid was also transmitted if there was any precipitation in the MSD area.

SECTION 3

RADAR-RAINFALL OPERATIONS

The real-time monitoring and forecasting of quantitative precipitation amounts using radar requires that a total system be assembled. For the CHAP experiment the basic elements of the radar-rainfall system were:

- 10-cm radar equipped with a digital processor and a minicomputer;
- real-time rainfall data obtained from 22 telemetered MSD raingages;
- a communications link between the radar operation center (near Joliet) and MSD to obtain telemetered rainfall amounts from MSD and to transmit to MSD, in real-time, the monitored and forecasted rainfall data for the city and its sub-areas;
- current weather information for alerting observing personnel of potential operations, providing long range (>6 hours) forecasts of potentially heavy rain events, and alerting the operator about potential changes in weather conditions during an operation and;
- staff to operate the system including adjusting the objectively derived rainfall amounts and forecasts, when necessary.

Except for the 22 telemetered raingages and the printer at MSD to receive results from the radar, all personnel and equipment were situated at the radar facility located 40 miles southwest of the center of Chicago (Fig. 6). In this section, each element and how it functioned within the total system is discussed, and an example of how the total system functioned on a rain day is provided.

Radar-Rainfall System

The general flow of data from the start of rain return at the HOT radar is illustrated in Fig. 7. Once a storm was in range of the HOT radar the objective features of the radar-rainfall system provided detailed information using objective analysis schemes. The digital processor and the minicomputer converted the analog signal from the radar to radar-indicated rain rates. If the storm was over the raingage network, these rain rates were adjusted by ground-truth data from the telemetered raingages. (This portion of the demonstration project did not function properly during the summer of 1979 due to a faulty microprocessor.) These radar-indicated and/or adjusted rainfall amounts were accumulated for a 30-minute period and after each 30-minute period were added to a 2 × 2 mi grid covering 16,384 mi^2.

Every 10 minutes the computer objectively produced a representation of the cells within the grided areas. These cells were matched with cells from the preceding 10-minute period by the operator. The minicomputer would then compile various statistics for each convective entity, and proceed to the forecast program. For each convective entity or cell which threatened to move across the Chicago region, a check of the various rainfall statistics was made by the operator to

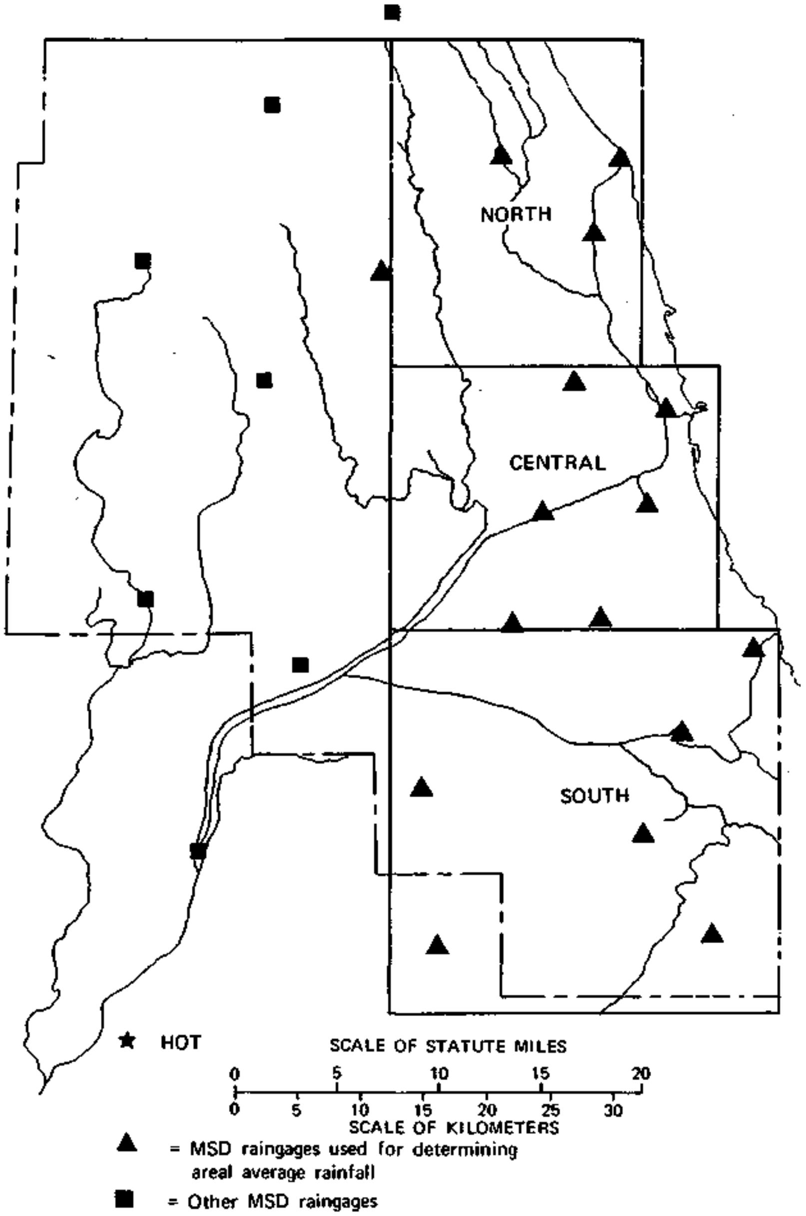


Figure 6. CHAP Monitoring and Forecasting Areas.

insure their validity. If there were any unrealistic values the operator, at this juncture, adjusted the cell statistics.

After various cell characteristics were adjusted the expected rainfall amounts for the next 30, 60, and 120 minutes for the north, central, and south sections of the Chicago forecast area (Fig. 6) were calculated. These forecasts were modified by the operator, if necessary, and transmitted to MSD. Modifications of the objective forecasts were made using current weather information obtained from the National Weather Service by two teletype circuits and a facsimile machine. The current weather data provided the operator with real-time information about changing weather conditions which could be used to alter the objective quantitative precipitation forecasts. This real-time weather data also served to alert personnel and MSD about the possibility of precipitation, both heavy and light.

A Case Study as an Example

The importance of understanding the prevailing synoptic weather situation is underlined in the following example for operations on 30 July 1979. Heavy rains often accompany weather features which are identified by the surface and upper-air networks maintained by the National Weather Service. Fronts and strong upper-air impulses associated with large amounts of moisture and instability in the low-levels of the atmosphere are often indicators of potentially heavy rainfall. The early morning hours of 30 July provided this type of situation. A description of the large-scale weather and the performance of the radar-rainfall system is provided in the following paragraphs.

Synoptic Weather Conditions. At 1900 CDT on 29 July 1979 a warm front extended from northeast Nebraska through north-central Iowa to east-central Illinois and southwest Indiana (Fig. 8). The principal shortwave trough moved into the western plains at 1900 CDT, and associated convective activity developed during the afternoon over eastern Nebraska and western and central Iowa along the warm front. By 0100 CDT on July 30, the strongest thunderstorm activity was situated over northeast Kansas, eastern Nebraska, and extreme western Iowa, although convective activity was forming in southern Minnesota and Illinois.

The warm front moved into extreme northern Illinois by 0700 CDT on July 30 (Fig. 8). Surface dew point temperatures were generally 70-75°F, while 850-mb dew points reached or exceeded 15°C in a 300-mi wide band from southwestern Missouri to northern Minnesota. The primary short wave extended from the North Dakota-Minnesota border south to central Kansas at 700 mb, and thunderstorm activity occurred in advance and as far east as Indiana. The strongest thunderstorms were located in eastern Iowa, northwest Illinois, and northwest Missouri.

Atmospheric conditions were generally supportive of thunderstorm activity over northern Illinois during the morning of 30 July. The upward vertical motion generated by the upper air trough was enhanced by the presence of a warm front, and moisture values at the surface and in the low levels of the atmosphere were 1 to 2 standard deviations above normal. Sounding information suggested that the atmosphere was conditionally unstable and needed only a 'triggering mechanism' to initiate thunderstorm activity. The warm front at the surface and the upper-air short wave provided the convective 'trigger' for this rain event.

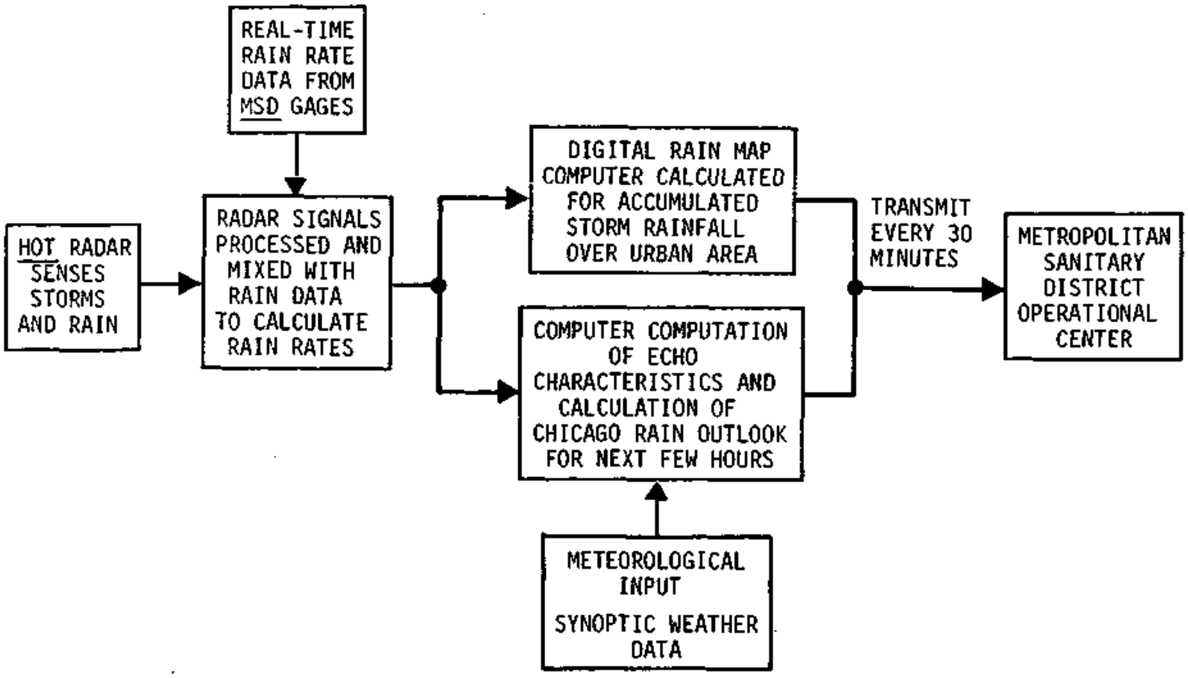


Figure 7. Radar-Rainfall Monitoring and Prediction Scheme Developed in CHAP.

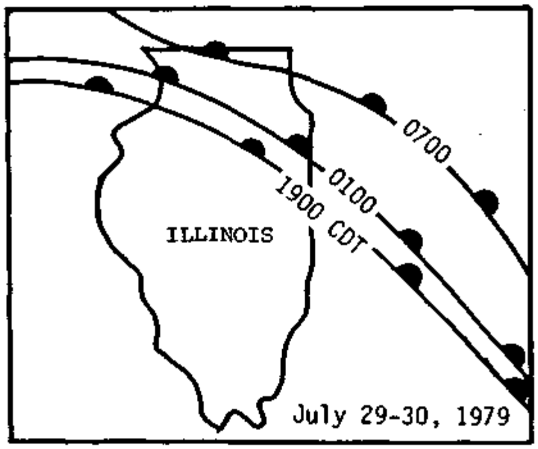


Figure 8. Warm Front Positions 29-30 July 1979.

The forecast by conventional data sources at midnight on 30 July indicated the potential of heavy shower and thunderstorm activity in northeast Illinois until noon. Light rain activity was noted by radar in the vicinity of the warm front until 0030-0100 CDT on 30 July. Radar echoes reformed between 0330 and 0400 CDT, approximately 70 mi northwest of Chicago (Fig. 9a).

This convective activity dissipated and new shower and thunderstorm activity formed 80 mi southwest of Chicago along the warm front at 0430 CDT (Fig. 9b). The development of the shower and thunderstorm activity from 0400 to 0630 CDT is shown in Fig. 9. Radar-indicated rainfall amounts are shown at 30-minute intervals over the 128 x 128 mi HOT radar display. Some light shower activity was observed over the extreme southern reaches of the Chicago forecast region between 0430 and 0500 CDT. This activity moved east, beyond the forecast region by 0600 CDT.

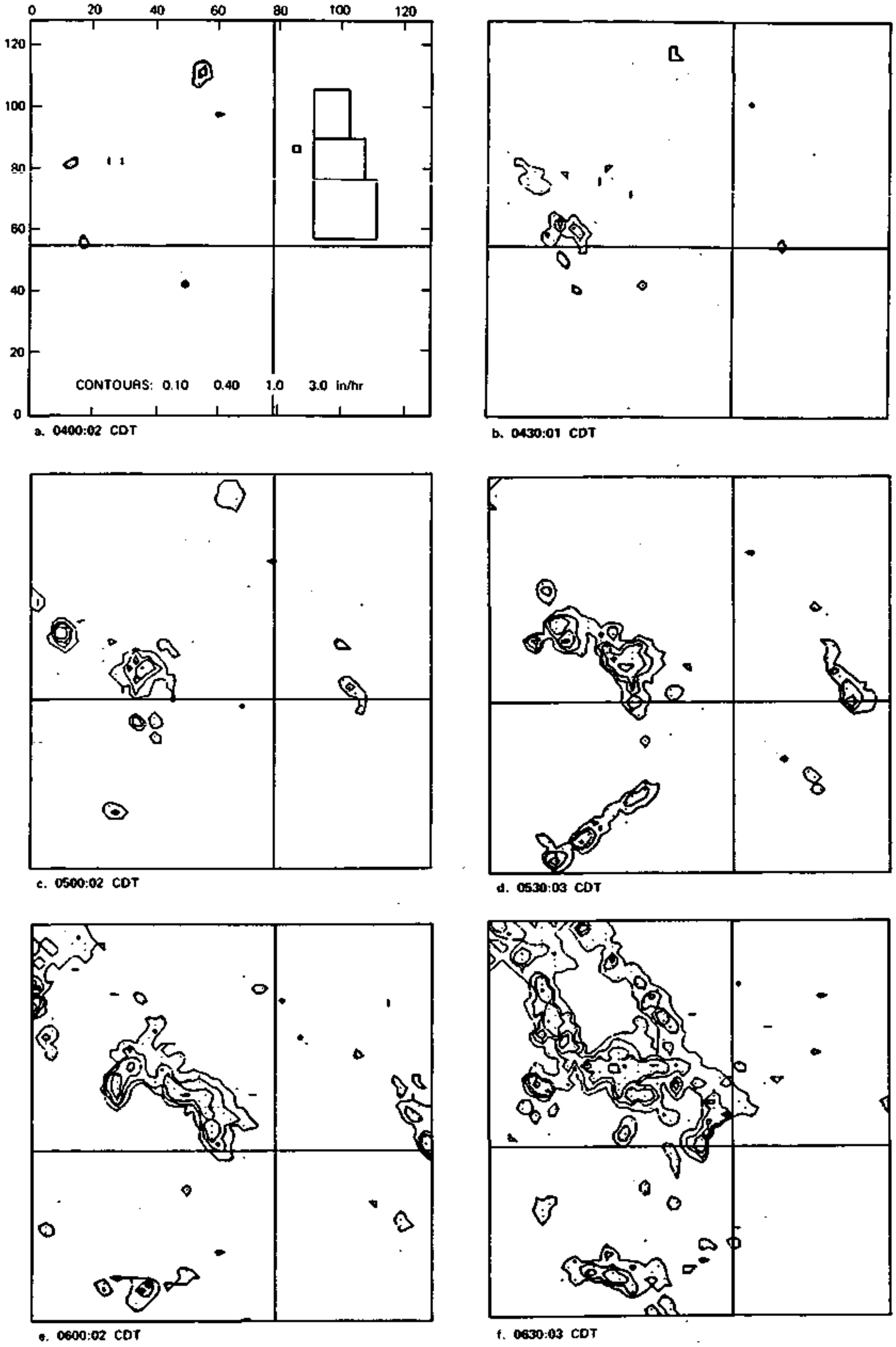
The shower and thunderstorm activity associated with the warm front moved northeast while growing steadily in areal coverage and intensity, and by 0630 CDT was approaching the western and southern portions of the Chicago forecast areas (Fig. 9f). These displays, as well as 30-minute accumulated rainfall and total accumulated rainfall, were available to the operator for real-time use.

Operations. All radar-indicated rainfall amounts and forecasts issued on 30 July were based upon the CHAP Z-R relation. The micro-processor at MSD was not functioning correctly, and the accumulated rainfall totals from the MSD raingages were not used as input to adjust the radar-indicated rainfall. Consequently, the only rainfall fields available to the operator were those produced by the radar in real-time.

The first non-zero forecast, issued at 0500 CDT, indicated that the rains would be measurable over the north, central, and south forecast regions by 0700 CDT. This forecast was 30 minutes early for the central and south sections, and an hour early for the north section. The first 30-minute forecasts were issued at 0700 CDT for verification at 0730 CDT.

The 0700 CDT forecasts were issued using the cell-tracking routine with data from 0650 and 0700 CDT (Fig. 10). The shower and thunderstorm activity continued to move northeast and was now just west of the Chicago region. Some light shower activity, in advance of the major rains, initiated over the central and extreme eastern parts of the forecast region, and new growth was noted over the southern parts of the observation grid. The cells were matched by the operator as shown on the bottom of Fig. 10. For example, echoes 3, 6, 10, and 11 at 0700 CDT were identified as new echoes. Echo 4 at 0650 CDT was matched with echo 8 at 0700 CDT, and so forth. The only merger occurred when echoes 6 and 7 at 0650 CDT combined to form echo 12 at 0700 CDT. After the matching was completed statistics for the individual echoes were printed (Table 7). The smaller echoes were moving northeast between 11 and 29 mi/hr, and the larger echoes were moving southeast or east-southeast at 16 to 24 mi/hr. The more southeasterly movement of the major rain cell (8) was due to growth on the southern and western flanks of the large rain area. This shifted the center of mass which was used to determine the cell movement.

After the cell tracking was completed, the forecast program was called. An example of an individual cell and the data presented to the operator is shown in Fig. 11. Each cell identified by the operator during the cell tracking was



a. 0400:02 CDT

b. 0430:01 CDT

c. 0500:02 CDT

d. 0530:03 CDT

e. 0600:02 CDT

f. 0630:03 CDT

Figure 9. Radar Echoes 30 July 1979 from 0400 to 0630 CDT.

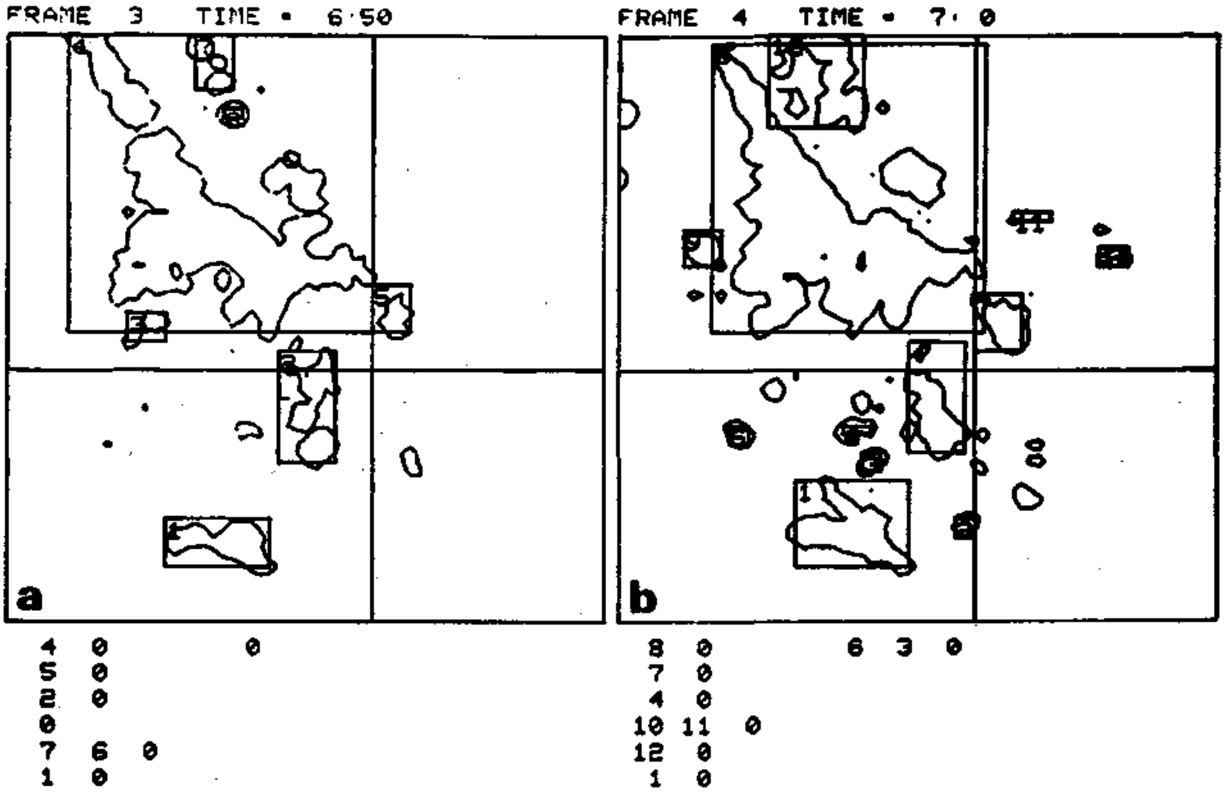
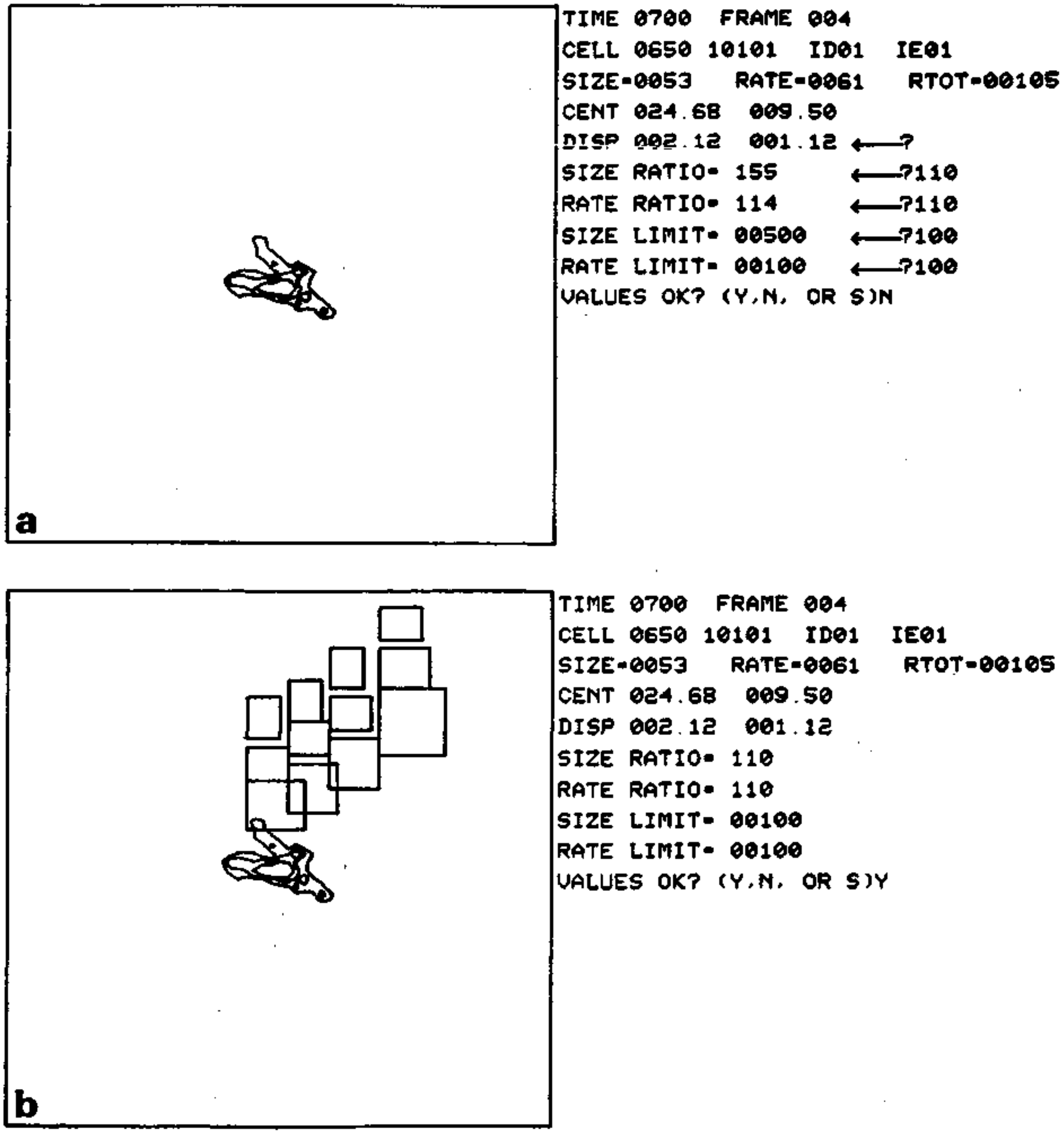


Figure 10. Radar Echoes on 30 July 1979 for Cell Tracking a) 0650 CDT and b) 0700 CDT.



```
TIME 0700  FRAME 004
CELL 0650 10101  ID01  IE01
SIZE=0053   RATE=0061   RTOT=00105
CENT 024.68  009.50
DISP 002.12  001.12 ←—?
SIZE RATIO= 155      ←—?110
RATE RATIO= 114      ←—?110
SIZE LIMIT= 00500    ←—?100
RATE LIMIT= 00100    ←—?100
VALUES OK? (Y,N, OR S)N
```

```
TIME 0700  FRAME 004
CELL 0650 10101  ID01  IE01
SIZE=0053   RATE=0061   RTOT=00105
CENT 024.68  009.50
DISP 002.12  001.12
SIZE RATIO= 110
RATE RATIO= 110
SIZE LIMIT= 00100
RATE LIMIT= 00100
VALUES OK? (Y,N, OR S)Y
```

Figure 11. Example of Forecasting Procedure a) Initial Parameters and Operator Input b) Final Parameters and 30-, 60-, 90-, and 120-minute Forecasts.

Table 7. Output from Cell-Tracking Program at 0700 CDT on 30 July 1979.

```
Frame 44   Time = 700
                                                                     HEADING    SPEED    CHANGE FACTORS
IDENT         IE     X     Y     SIZE     RATE     VOL      STATUS       DEGREE      MPH     AREA   INTENSITY
650  20907     0    21    60       14       37      21    Lost Merge
650  21006     0    23    54        6       43      10    Lost Merge
700  30912    12    22    58       58       36      32    New Merge         59       11      290         92
630  30601     1    25    10       53       61     513    Old Echo          62       29      155        114
650  30402     4    34    22       39       53     136    Old Echo         104       24      102        104
650  20304     8    22    42      347       69     874    Old Echo         126       16      110        120
650  20805     7    41    31       22       60      34    Old Echo         148       17      157        237
700  10103     3    27    17        7       31       0    New Growth
700  10205     5    13    20        7       58       0    New Growth
700  10506     6    25    21        7       47       0    New Growth
700  10709     9     9    40       12       64       0    New Growth
700  11010    10    52    39        6       17       0    New Growth
700  11111    11    44    43        7       17       0    New Growth
```

presented individually to the operator. The cell-tracking routine outlined only the 0.16 in/hr isohyet (Fig. 10), but the forecast program presented the more detailed structure of each cell centered within the 128 x 128 mi grid (Fig. 11). As each echo was presented, the operator had the option of either accepting (Y), rejecting (N), or skipping (S) the echo. The first echo chosen by the operator to have a possible impact upon the forecast region of Chicago was identified as echo IDO1. The operator checked the displacement or movement, increases or decreases in areal growth (size) or rain rate, and the size and rate limits. The size and rate limits place an upper bound on the area and on the intensity of the average rain rate during a forecast period for each cell. The operator has the option of changing any of these parameters to make them compatible with the present weather situation. This particular cell was a new cell, formed at 0650 CDT. Consequently, rapid increases of area and rain rate occurred in the intervening 10 minutes. The average rain rate increased from 0.53 to 0.61 in/hr, and the area increased from 136 to 212 mi^2. Such behavior of a new echo was common during the early growth of a vigorous echo, but such behavior would not be sustained over the next two hours. Thus, the operator altered the values for the size ratio and rate ratio, and imposed a size limit of 100 units, or limited the growth of this rain cell to (400 mi^2) during the next two hours. The panel was repeated (Fig. 11b), and upon accepting all the parameters, the relative position of the rain cell with respect to the forecast area for the next 30, 60, 90, and 120 minutes was shown. Similarly, each cell was in its turn either rejected, accepted, or skipped by the operator, and a final forecast incorporating all cells was made.

The forecast at 0700 CDT and verification for 0730, 0800, and 0830 CDT are given in Table 8. The verification for the northern and central sections were made with the dense raingage network (one gage per 9 mi^2), but the verification for the southern sections was done using seven gages in or surrounding the southern section (Fig. 6). The southern extension of the dense raingage network indicated a band of heavy rainshowers, which was not detected by the less dense MSD network. Consequently, the verification data for the southern section may be somewhat low on 30 July, and point out the problems of verifying radar monitored and forecast rainfall values in this section. The forecast indicated that light rains (0.01 to 0.04 in) would be measured over the forecast regions by 0730 CDT. Raingages at 0730 CDT did indicate that light rains fell within all the forecast regions. However, the rains in the northern section were not intense or widespread enough to average 0.01 in. The 30-minute forecast for the central and southern sections were accurate and there was zero forecast error. The 60-minute forecast for the north and central section were within 0.05 in. Overestimates were made in all three regions; the highest overestimate was in the southern section which had a difference of 0.31 in. The 120-minute forecast was also high for the southern section. The 120-minute forecast for the central section was within 0.07 in. The 120-minute forecast for the north section had a difference of 0.32 in. Light rains were forecasted to continue in the northern section through 0900 CDT. However, by 0900 CDT 0.38 in of rain had accumulated over the northern section, of which 0.32 in occurred in the 30-minute period from 0830 to 0900 CDT.

Tables 9 and 10 give the verification of the objective man-made forecasts for the individual 30-, 60-, and 120-minute periods and the accumulated 30-, 60-, and 120-minute periods on 30 July 1979 from 0600 to 1200 CDT. The average error for the individual forecasts showed an increase with forecast time. The average

Table 8. Forecast at 0700 CDT and Verification for North, Central, and South for the Next 30, 60, and 120 Minutes.

North		Central		South	
Forecast (in)	Verification (in)	Forecast (in)	Verification (in)	Forecast (in)	Verification (in)
30 Minutes					
0.01	Trace	0.01	0.01	0.04	0.04
60 Minutes					
0.03	0.02	0.08	0.03	0.51	0.20
120 Minutes					
0.06	0.38	0.63	0.56	1.70	0.82

Table 9. Verification of Radar Forecasts with Individual 30, 60, and 120 Minute Rainfall Amounts for 30 July 1979.

		All Forecasts		Forecasts or Area Rains ≥0.1 in	
	Minutes	Average Differences (in)	Average Percent Differences	Average Error (in)	Average Percent Error
North	30	0.03	23	0.15	42
	60	0.04	29	0.11	22
	120	0.21	239	0.35	254
Central	30	0.03	29	0.09	49
	60	0.05	41	0.10	34
	120	0.19	157	0.23	166
South	30	0.06	26	0.13	57
	60	0.13	50	0.24	75
	120	0.22	60	0.33	65

difference had a range from 0.03 to 0.06 in for the 30-minute forecasts, 0.04 to 0.13 in for the 60-minute forecasts, and 0.19 to 0.22 in for the 120-minute forecasts. The average percent error for the 30-minute forecasts ranged from 23 to 29%, the 60-minute forecasts ranged from 29 to 50%, and the 120-minute forecasts ranged from 60 to 239%. About half of the forecasts were for light rains producing less than 0.1 in. Thus, relatively small differences between the forecasted and observed amounts,- when divided by a small rainfall amount gave large percent errors. Forecasts of 0.1 in or more showed an increase in the average difference compared to all forecasts, and the average percent error for these forecasts was also greater.

Figure 12 shows the verification with time in graphical form for the individual 30-, 60-, and 120-minute forecasts for the central region compared to measurements on the dense raingage network. The forecasting routine at 0730 and 0800 CDT did not function correctly and either gave forecasts of zero or the forecasts were missing. The operator was able to compensate for these problems and make the quantitative forecasts. These forecasts are shown on Fig. 12 by a dashed line.

Excellent agreement was found between the 30- and 60-minute forecasts and the rains indicated by the dense raingage network. The forecasts followed the actual time change of rain well, showing the peaks and dissipation of the rain over the central forecast region. The objective 120-minute forecast did a good job, with some overestimation in the early stages of the rain. The operator's forecasts for 120 minutes were low; however, the 30- and 60-minute forecast made by the operator was good. This incident illustrates the need for a skilled operator to monitor, update, and alter the results, when necessary, of the objective analysis scheme.

Table 10 shows the verification of the forecasts for the accumulated 30-, 60-, and 120-minute forecasts periods on 30 July 1979. The average difference for all forecasts increased as the forecast period was extended. For the 30-minute forecast the average difference ranged from 0.07 to 0.14 in, while the average error for the 120-minute period ranged from 0.18 to 0.25 in. Similar results were obtained for all those accumulated forecasts equal to or in excess of 0.2 in.

In general, radar by itself is a poor indicator of quantitative rainfall amounts at the ground unless the radar-indicated rainfall field is adjusted by surface raingage data. However, on 30 July 1979 the CHAP rainfall equation worked well. Consequently, the radar-indicated rainfall fields provided satisfactory quantitative measures of the monitored rainfall at the ground.

Table 11 presents the verification of the 30-minute radar indicated rainfall amounts for 30 July 1979. The average difference from the monitored and the measured rain at ground varied from 0.02 to 0.05 in. The average percent error ranged from 12 to 84%. For those radar-indicated or average network rainfalls greater than or equal to 0.05 in, which are the more hydrologically significant rainfalls, the average differences ranged from 0.04 to 0.13 in and the average percent error ranged from 17 to 48%. In general, the average percent error for the heavier rains was less than the average percent error for all rains from 0700 to 1200 CDT.

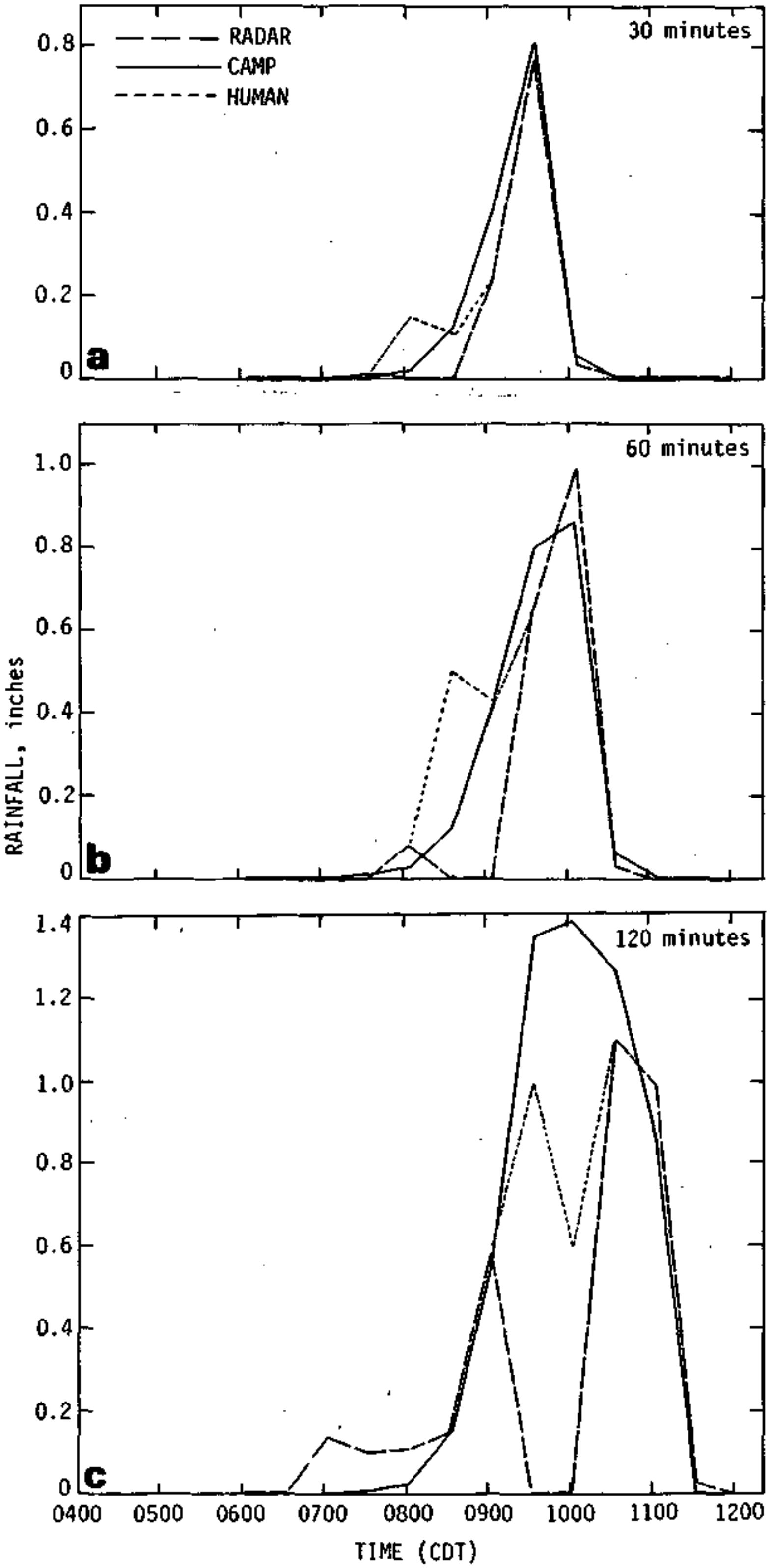


Figure 12. Verification of 30-minute Forecasts for Central Area on 30 July 1979.

Table 10. Verification of Radar Forecast for Accumulated 30, 60, and 120 Minute Forecast for 30 July 1979.

	All Forecasts			Forecasts or Area Rains ≥0.2 in	
	Minutes	Average Differences (in)	Average Percent Differences	Average Error (in)	Average Percent Error
North	30	0.07	35	0.10	16
	60	0.07	35	0.09	16
	120	0.18	67	0.23	35
Central	30	0.12	73	0.15	16
	60	0.17	139	0.17	139
	120	0.24	134	0.30	22
South	30	0.14	27	0.16	22
	60	0.20	43	0.20	43
	120	0.25	34	0.29	38

Table 11. Verification of 30-Minute Radar-Indicated Rainfall Amounts for 30 July 1979 from 0700 to 1200 CDT.

	North	Central	South
Average Difference (in)	0.04	0.05	0.02
Difference Range (in)	-0.21 to 0.08	-0.19 to 0.06	-0.11 to 0.01
Average Percent Error	84	67	12
Range Percent Error	-66 to 400	-46 to 300	-50 to 3
	Radar-Indicated or Raingage Amount ≥0.05 in		
Average Difference (in)	0.13	0.10	0.04
Difference Range (in)	-0.21 to -0.04	-0.19 to -0.04	-0.11 to 0.01
Average Percent Error	38	48	17
Range Percent Error	-66 to -10	-46 to -100	-31 to 3

The accuracy of the radar-indicated accumulated rainfall amounts for 30 July 1979 are given in Table 12. The average difference ranged from 0.06 to 0.11 in, and the percent error ranged from 14 to 98%. For accumulated rains of greater than 0.1 in the average difference was 0.05 to 0.14 in and the average percent error was 9 to 13%.

These errors provide a reasonable approximation of those that can be expected from radar-indicated rainfall amounts when the rainfall field is unadjusted by ground-truth raingages. It is anticipated that if the radar-indicated rainfall field on 30 July had been adjusted by ground-truth the error in the radar-indicated rainfall amounts would be substantially less.

Table 12. Verification of Radar-Indicated Accumulated Rainfall for 30 July 1979 from 0700 to 1200 CDT.

	North	Central	South
Average Difference (in)	0.06	0.11	0.11
Difference Range (in)	-0.14 to 0.11	-0.24 to 0.08	-0.17 to 0.03
Average Percent Error	83	98	14
Range Percent Error	-26 to 500	-27 to 700	-21 to 25
	Radar-Indicated or Raingage Amount ≥0.2 in		
Average Difference (in)	0.05	0.14	0.13
Difference Range (in)	-0.14 to 0.01	-0.24 to -0.08	-0.17 to 0.0
Average Percent Error	9	13	13
Range Percent Error	-26 to 1	-27 to -6	-21 to 0

SECTION 4

MONITORING AND PREDICTION DURING DEMONSTRATION

Introduction

The radar-rainfall system was designed to monitor and forecast quantitative precipitation amounts, and separate evaluations were made of these two functions. The primary evaluation tool for both,was the Survey's dense recording raingage network (Fig. 4), supplemented by the MSD raingage network (Fig. 6). The three areas (north, central, south) for forecasting and monitoring of rainfall were not defined by MSD until May 1979, after the installation of the dense raingage network, and the southern area extended well beyond the southern boundary of the dense network. Consequently, it was only possible to evaluate the rain in the southern area with seven MSD gages within or near the boundaries of the area.

The demonstration period began on 18 June and ended on 15 August. During this period, 2832 transmissions of monitored and predicted rain amounts were possible with transmission every 30 minutes from the HOT radar site to MSD. Nearly 99% of these transmissions were made, and missing transmissions occurred during only four rain events. These were due to a severed telephone line, a power failure due to a lightning strike, and minor breakdowns of the radar-rainfall system. Fortunately, the power loss experienced with the lightning strike occurred after heavy rains had moved across the three areas. Thus, most of the rains were monitored and the forecasts adequately described the remaining rain period. Routine maintenance of the radar-rainfall system was accomplished on days when no rain was expected in the forecast region.

The radar-rainfall system worked well during the demonstration, except for a microprocessor designed to accumulate 30-minute and daily rainfall totals gathered by the MSD telemetered raingages. Data from these gages were collected every 30 minutes by the minicomputer at the HOT radar site. The processor problem prevented implementation of the scheme, adopted from Brandes (1975) and modified for application in real-time operations, which would adjust the radar-indicated rainfall at frequent intervals during each storm through use of telemetered rainfall data from the MSD network. This adjustment procedure would substantially improve the accuracy of the radar-measured rainfall rates for reasons discussed elsewhere in this report, and, thereby, make the system more useful in urban hydrologic operations. Part of the microprocessor problems were corrected by late July, but accurate rainfall totals still could not be collected from the MSD raingages. However, some of the MSD gages were operating satisfactorily by 31 July, so that this real-time raingage data could be used to improve the accuracy of the radar rainfall measurements during the period from 1 August to 15 August, and, thus, improve the quality of the prediction-monitoring activities to some degree.

Method of Evaluation

As a result of the above problems, the verification of the monitored and predicted rainfall amounts were divided into two groups. The first included all storms from the beginning of the demonstration period (18 June) to 31 July. This period is referred to as "June-July." The second period began on 1 August and ended 15 August, and is referred to as "August."

The predicted and monitored rainfall values provided to MSD included areal average rainfall amounts for the northern, central, and southern basins delineated by MSD. The evaluation of these monitored and forecasted amounts was done only for those periods when rain threatened or occurred over one of the three regions. The forecasts were evaluated from either two hours before a rainfall event began or from the time the first objective forecast indicated measurable rainfall in one of the forecast regions, whichever came first. The evaluation of the monitored rain amounts began from the time an areal rainfall amount of at least 0.01 in was measured by the raingages or the radar indicated an areal average of 0.01 in or more in any one of the three areas. Thus, those periods of no rain observed by the radar or by raingages were not tabulated. These untabulated forecasts and observations of zero, approximately 2100, were correct; but for the evaluation, only those monitored or forecasted amounts which were associated with rain or impending rain over the Chicago region were verified.

The evaluation of both the monitored and forecasted values was done by calculating the difference between the monitored or forecasted value and a control (C), usually the Water Survey dense raingage network or the MSD network. The network measurements of areal mean rainfall were assumed to be the "true" rainfall. Thus, the difference between the network and the monitored or predicted rainfall was defined as the monitoring or forecasting error. The errors were calculated using

$$\text{ERROR} = A - C \ ,$$

where A is the monitored or predicted rainfall amount and C is the network amount. The sign of this difference was also retained, so that the verification would reveal whether there were consistent over- or underestimations of the monitored or forecasted values.

In addition, the percent difference of each monitored or forecasted value was determined using the following formula

$$\text{Percent error} = \frac{A-C}{C} \times 100 \ .$$

The sign of the percent error was again retained. If no rain fell within the monitoring or forecasting period and a monitored or forecasted value was made, the percent error was infinity. Also, if a zero amount was forecasted or observed (monitored) and measurable rain fell within the network according to the control being used, the percent error was a negative 100%. Small differences associated with low rainfall amounts can produce high percent errors. For example, if a monitored or forecasted amount was 0.05 in and the actual control rainfall was 0.01, the difference or error would be 0.04 in, but the percent error would be 400%. Thus, it was considered desirable to verify using both the error and percent error.

Rainfall Distribution

The rainfall from the dense raingage network during the demonstration period was analyzed to determine the distribution of 30-minute and accumulative rainfall amounts for guidance in later analyses and interpretation of results. Since the verification period was divided into June-July and August, the rainfall analysis over the raingage network was divided similarly. Accumulative and 30-minute averages of rain were obtained for each 30-minute period in which rain fell in at least one raingage, and the averaging continued throughout the storm. During the demonstration period, 343 periods of 30-minute and accumulative rain were averaged. Results are summarized in Tables 13-15.

More than 50% of the 30-minute rain periods in June-July and August averaged less than 0.01 in of rain (Table 13). Less than 10% had amounts equalling or exceeding 0.10 in, and these are the only intensities that are usually important to the urban hydrolegists during heavy rainstorm operations. Less than 2% of the 30-minute periods had moderate intensities exceeding 0.30 in. None exceeded 1.00 in in 30 minutes. Thus, analyses and conclusions had to be based upon a very limited sample of hydrologically-important rain intensities, due to the short demonstration period and relatively few natural occurrences of heavy storm rainfalls.

The distribution of accumulative rainfall amounts as a percentage of the total observations is shown in Table 14. Accumulative amounts are the total rainfall amounts for the storm at the end of each individual 30-minute period. Table 14 shows that rainstorms tended to be more intense in August. For example, approximately 47% of the accumulations in August equalled or exceeded 0.10 in compared to 33% in June-July. Similarly, approximately 25% of the August accumulations equalled or exceeded 0.50 in compared to 7% in June-July.

Table 15 shows the percentage distribution of maximum point rainfall during the two sampling periods, and provides further evidence of the greater intensity of August storms. Thus, 46% of the August maximums exceeded 0.50 in compared to 41% in June-July, and 31% of the August maximums exceeded 1.00 in compared to 26% in the June-July storms.

A measure of the areal extent of the 1979 storms is the percent of time rain occurred in either the northern or central section, but not in both. During June-July, 42% of the storms had no rain in one section when it occurred in the other. However, during August rain was not recorded in the northern section for only 7% of the storms and in the central section for only 24% of the storms. The average rain for each storm during June-July was 0.17 in, compared to 0.31 in in August. Overall, the rainfall analysis indicated that many light scattered rainstorms occurred during June-July intermingled with heavier, more general rains. The August storms were characterized by heavier, widespread rainfall.

Table 13. Percentage Distribution of 30-Minute Average Rainfall in June-July and August.

	Rainfall Amounts (Inch)					
	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99
June-July	65.5	22.5	6.8	3.2	0.5	1.6
August	57.4	21.5	10.3	7.0	2.5	1.3

Table 14. Percentage Distribution of Accumulated Average Rainfall in June-July and August.

	Rainfall Amounts (Inches)									
	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5
June-July	40.0	21.6	5.6	11.5	6.3	7.7	3.2	1.1	2.9	0.0
August	31.8	16.5	5.0	9.1	7.0	5.8	9.9	12.0	1.7	1.2

Table 15. Percentage Distribution of Maximum Gage Rainfall in June-July and August.

	Rainfall Amounts (Inches)					
	≤0.10	0.11-0.25	0.26-0.50	0.51-1.00	1.01-2.00	>2.0
June-July	25.9	25.9	7.4	14.8	14.8	11.1
August	7.7	30.8	15.4	15.4	23.1	7.7

SECTION 5

VERIFICATION OF MONITORING

During the CHAP demonstration period, monitored values of quantitative rainfall amounts were obtained for 30-minute periods and for the accumulated rainfall during each storm. Quantitative amounts were obtained from 1) the dense raingage network which encompassed the northern and central sections, 2) the MSD telemetered raingage values, 3) the radar-indicated rainfall, and 4) the man-machine estimates of rainfall. During the demonstration period the radar-indicated rainfall amounts were calculated using the Z-R equation derived as part of the CHAP studies. Very detailed analyses were made of each of the above four rainfall parameters. The standard of comparison for the MSD network and other evaluations was the dense network operated by the Water Survey in the Chicago urban area during the demonstration period. Based on extensive raingaging studies by Survey, which has operated dense networks in Illinois for the past 30 years, the Chicago network with gages spaced approximately 3 miles apart should provide accurate measurements of the "true" mean rainfall, point maximum rainfall, areal extent of rainfall and other rainfall parameters for sampling periods of 30 minutes or longer used in the CHAP studies.

The various detailed analyses have been summarized in the form of tables which are part of Appendix A to this report. In the following paragraphs, a brief summary of the highlights of these analyses is provided, and the reader is referred to the Appendix for more detailed data and information.

30-Minute Monitored Rainfall

MSD Gage Network. Initially, an analysis was performed to determine the accuracy of monitored rainfall amounts available from the MSD telemetered network. This information is useful in establishing telemetering needs for urban operations, since the MSD network with gages spaced about 6 miles apart is a good example of a relatively dense urban network. Furthermore, evaluation of the MSD network is helpful in evaluating the applicability of radar and man-machine combinations for monitoring and prediction in urban real-time operations.

Table 16 provides a brief summary of the MSD network evaluation. All data have been combined to provide a frequency distribution of measurement errors in the north and central sections during June-August 1979. Values are accumulated from left to right in this and the following Tables. The frequency of errors of various magnitude are shown for several groups or classes of areal mean rainfall for 30-minute periods within storms. For example, with areal means of 0.10 to 0.19 in, there were 31 samples and the MSD measurement errors ranged from 0 to 1 ess than 0.24 in. Of the 31 cases, 15 (48%) were 0.04 in or less, and 24 (77%) had errors of 0.10 in or less.

Inspection of Table 16 shows that if a very high degree of accuracy in mean rainfall measurement is required for short intervals, such as 30 minutes, the MSD network is probably not adequate. However, for real-time hydrologic operations in which an error of the order of 0.10 in is usually not critical, the network can provide a very useful telemetering service for real-time operations. CHAP studies and others made in recent years indicate that this error distribution can be improved upon by use of 10-cm radar in conjunction with adequate telemetered gages to adjust the radar-indicated rainfall for various types of errors that are inherent to such systems in the quantitative measurement of rainfall.

Unadjusted Radar Measurements. As indicated earlier, a microprocessor problem prevented adjustment of the radar-indicated rainfall rates with telemetered raingage data through use of the modified Brandes technique developed as part of the CHAP research. Table 17 shows the frequency distribution of errors with the unadjusted radar observations of the 10-cm, FPS-18. The contents of the table are the same as Table 16.

For very light rainfalls (0.01-0.04 in), the radar accuracy is approximately equivalent to the MSD network, which is a relatively dense urban network as pointed out earlier. However, for moderate 30-minute rainfalls (0.10-0.19 in), the radar accuracy is less than that of the MSD network. Thus, only 24% of the radar errors for areal means of 0.10 to 0.19 in were 0.04 in or less, compared to 48% for the MSD network. With areal means of 0.30 in or more, 43% (9) of the radar cases had errors in the range from 0.25 to 0.49 in. The majority of these exceeded 100%.

The distribution of errors with the unadjusted radar measurements in Table 17 shows the need for an adjustment procedure to maximize the benefits of radar in real-time, prediction-monitoring of heavy rainstorms. This has been stressed in earlier CHAP reports (Huff et al., 1978) and by other investigators, such as Wilson (1976).

Man-Machine Monitoring

At the present stage of technological development, it was concluded earlier in the CHAP research that a combination of man and machines was needed to optimize the real-time, prediction-monitoring system developed for the Chicago urban area (discussed elsewhere in this report). This requires an experienced radar meteorologist to examine, evaluate, and adjust when necessary, the computer output pertaining to movement, intensity, rainfall volume and other pertinent factors derived from radar observations of the storm echo field.

The frequency distribution of errors with the man-machine combination used during June-August 1979 is summarized in Tables 18 and 19. The June-July and August distributions have been separated, because some telemetered raingage data was available to the duty meteorologist for adjusting the radar echo intensities during August. The August sample was much smaller than that for June-July, so only limited comparison can be made between the two periods.

Inspection of Tables 18 and 19 does indicate (as expected) that the errors become smaller as telemetered data become available for adjusting the radar-indicated rainfall. Thus, for computed means of 0.10 to 0.19 in, the error was equal to or less than 0.04 in in 69% (18/26) of the cases in August compared with 25% (12/48) in June-July, when no telemetered raingage data were available. Similarly, 75% (6/8) of the errors for means of 0.20-0.29 in were equal to or less than 0.10 in in August compared to 50% (8/16) in June-July.

Table 16. Frequency Distribution of MSP Network Errors in Monitoring 30-Minute Rainfall during June-August in North and Central Sections.

Computed mean (in)	Number of cases enveloped for given error (in)					
	0	≲0.04	≲0.10	≲0.24	≲0.49	≲0.99
0.01-0.04	32	121	123	125	125	126
0.05-0.09	8	41	53			
0.10-0.19	2	15	24	31		
0.20-0.29	0	2	5	6	8	
≳0.30	0	1	4	6		

Table 17. Frequency Distribution of Unadjusted Radar Measurement Errors in Monitoring 30-Minute Rainfall during June-August in North and Central Sections.

Computed mean (in)	Number of cases enveloped for given error (in)					
	0	≲0.04	≲0.10	≲0.24	≲0.49	≲0.99
0.01-0.04	17	216	217			
0.05-0.09	0	32	56			
0.10-0.19	0	9	30	37	37	38
0.20-0.29	0	1	5	25		
≳0.30	0	1	5	12	21	

Table 18. Frequency Distributions of Man-Machine Errors in Monitoring 30-Minute Rainfall during June-July in North and Central Sections.

Computed mean (in)	**Number of cases enveloped for given error (in)** **≤0.04**	**≤0.10**	**≤0.24**	**≤0.49**	**≤0.99**
0.05-0.09	8	13			
0.10-0.19	12	46	47	47	48
0.20-0.29	2	8	16		
≥0.30	0	3	10	13	14

Table 19. Frequency Distribution of Man-Machine Errors in Monitoring 30-Minute Rainfall during August in North and Central Sections.

Computed mean (in)	**Number of cases enveloped for given error (in)** **≤0.04**	**≤0.10**	**≤0.24**	**≤0.49**	**≤0.99**
0.10-0.19	18	24	26		
0.20-0.29	1	6	8		
≥0.30	0	2	3	3	5

Table 20. Frequency Distxibution of MSP Network Errors in Monitoring Accumulated Rainfall during June-August in North and Central Sections.

Computed	Number of cases enveloped for given error (in)					
mean (in)	**0**	**≤0.04**	**≤0.10**	**≤0.24**	**≤0.49**	**≤0.99**
0.01-0.04	9	94	97	98	107	
0.05-0.09	2	18	33	35		
0.10-0.19	3	53	59	60		
0.20-0.29	0	26	54	60	63	
0.30-0.49	0	7	31	58	63	
0.50-0.99	0	3	17	49	57	60
≥1.00	1	5	5	16		

Table 21. Frequency Distribution of Unadjusted Radar Measurement Errors in Monitoring Accumulated Rainfall during June-August in North and Central Sections.

Computed	Number of cases enveloped for given error (in)						
mean (in)	**0**	**≤0.04**	**≤0.10**	**≤0.24**	**≤0.49**	**≤0.99**	**≤1.50**
0.01-0.04	5	167	170	170	178	184	
0.05-0.09	0	15	77				
0.10-0.19	0	3	18	56	64		
0.20-0.29	0	1	5	53	57		
0.30-0.49	0	0	0	29	38		
0.50-0.99	0	2	5	12	46	75	
≥1.00	0	0	0	6	22	83	98

Table 22. -Frequency Distribution of Man-Machine Errors in Monitoring Accumulated Rainfall during June-July in North and Central Sections.

Computed	Number of cases enveloped for given error (in)						
mean (in)	0	≤0.04	≤0.10	≤0.24	≤0.49	≤0.99	≤1.50
0.05-0.09	2	2	2	2	4		
0.10-0.19	21	21	82	82	86		
0.20-0.29	5	5	13	31	32		
0.30-0.49		11	9	14	18	21	
0.50-0.99	2	2	4	16	30	48	
≥1.00	0	0	3	7	10	35	49

Table 23. Frequency Distribution of Man-Machine Errors in Monitoring Accumulated Rainfall during August in North and Central Sections.

Computed	Number of cases enveloped for given error (in)						
mean (in)	0	≤0.04	≤0.10	≤0.24	≤0.49	≤0.99	≤1.50
0.10-0.19	12	12	14				
0.20-0.29	2	2	19				
0.30-0.49	8	8	9	12	13		
0.50-0.99	18	18	28	37	56	57	
≥1.00	0	0	0	11	17		

Comparison of the man-machine errors in Tables 18-19 with those for unadjusted radar in Table 17 provides evidence of the superiority of the man-machine combination. For example, combining Tables 18 and 19, the error in computed means of 0.10 to 0.19 in was equal to or less than 0.04 in in 41% (30/74) of the cases for the man-machine method compared with 24% (9/38) for the unadjusted radar estimate. Similarly, the error was 0.10 in or less in 95% (70/74) of the cases for the man-machine mix compared with 79% (30/38) with the unadjusted radar. The difference became more pronounced in the heavier rain intensities. Thus, for computed means of 0.20-0.29 in, the man-machine error was equal to or less than 0.10 in in 58% (14/24) of the man-machine cases compared with 20% (5/25) for the unadjusted radar computations. As pointed out earlier, the man-machine method was operating at less than maximum effectiveness during most of the demonstration period because telemetered raingage data were not available for guidance in the man-initiated adjustments of machine-computed rainfall intensities. Otherwise, the superiority of the man-machine mix in monitoring rainstorms would very likely have been even more pronounced.

Comparison of Tables 18 and 19 with Table 16 indicates that the man-machine method of monitoring was equivalent, if not slightly superior, to the relatively dense urban network operated by MSD. For computed means of 0.05-0.09 in, the man-machine error never exceed 0.10 in. For means of 0.10-0.19, the man-machine error was equal to or less than 0.10 in in 95% (70/74) of the cases compared with 77% (24/31) for the MSD network. When computed means were 0.20-0.29 in, the man-machine method had errors equal to or less than 0.10 in in 58% (14/24) of the samples compared to 62% (5/8) for the MSD network. With telemetered raingage data available to the duty meteorologist, it is anticipated that the man-machine mix would have exhibited a significant superiority.

Accumulative Rainfall Monitoring

The summary analyses presented in Tables 16-19 for 30-minute rainfall amounts was repeated for the accumulated rainfall amounts. As with the 30-minute amounts, very detailed analyses are presented in table form in the Appendix for those readers interested in a more thorough examination of the data and information obtained during the demonstration project.

Table 20 shows the frequency distribution of MSD network errors in monitoring accumulated rainfall amounts at 30-minute intervals throughout each storm. The same general trends, and, therefore, the same conclusions are reached as pointed out in the discussion of the 30-minute amounts summarized in Table 16. Note in Table 20 that the percentage error tends to decrease with increasing rainfall, which is pertinent to urban hydrologic. operations. For example, for accumulations of 1.00 in or more, the error never exceeded 0.24 in, (less than 25%) , whereas maximum errors of the same magnitude occurred with all the lighter amounts.

Table 21 shows the same trends as Table 17 with unadjusted radar measurement of rainfall amounts. That is, radar is approximately equivalent to the MSD network in the measurement of very light amounts, but the network is significantly superior in measuring moderate to heavy rain amounts.

Examination of Tables 22 and 23 supports the conclusion obtained from Tables 18 and 19 regarding the significant improvement in the man-machine measurements expected when telemetered raingage data are available to assist in adjustment of the radar-indicated rain rates. Thus, in August when some telemetered data were available to the duty meteorologist, accumulative amounts were measured with smaller errors than in June-July, and the improvement was most pronounced in the heavier rainfalls,- which are of primary interest to the urban hydrologist. For example, when computed means were 0.50-0.99 in, 49% (28/57) of the August means had errors of 0.10 in or less, whereas only 8% (4/48) were in this range in June-July storms. With accumulated amounts of 1.00 in or more, all August errors were less than 0.49 in, but in June-July only 20% (10/49) were less than 0.49 in.

Comparison of Tables 21-23 provides additional support for the earlier conclusion regarding the definite superiority of the man-machine monitoring over unadjusted radar measurements of surface rainfall. As one example, for accumulated amounts (computed areal means) in the range from 0.50 to 0.99 in, only 16% (12/75) of the radar measurements had errors equal or less than 0.24 in, compared with 33% (16/48) for June-July with no telemetered raingage data available to the duty meteorologist, and 65% (37/57) in August when part of the available telemetered data became available for guidance in adjusting the radar-indicated rain amounts. Comparison of Tables 20, 22, and 23 indicates that the MSD network errors in measuring accumulated rainfall amounts tended to be smaller than the man-machine combination in June-July, but about equivalent in August when some, but not all, of the telemetered data became available to the duty meteorologist.

SECTION 6

FORECAST VERIFICATION

Introduction

During the CHAP demonstration period two forecasts were made. The first predicted the amount of additional rain expected over the urban area in the next 30, 60, and 120 minutes during the progress of a storm. The second gave the anticipated accumulated rain amounts from the beginning of the storm with the end of the next 30, 60, and 120 minutes. Verification for both forecasts began from the time of the first non-zero forecast for one or more of the three areas, or two hours before an areal average of 0.01 in occurred in any of the areas.

During each storm, two forecasting methods were used. The first involved a semi-objective forecast that utilized the cell tracking sub-routine. The radar meteorologist first corrected computer-derived storm motions which were inconsistent with the expected movement of the storm (based on synoptic weather analyses), adjusted the rate of change of rain intensity and/or the areal size projected over the next 120 minutes; and then placed upper limits on the size and rain intensity of each cell. These changes were made on the basis of continuity of the rainfall system, experience, and knowledge of synoptic conditions. The adjustments (if any) were inserted into the computer which used them in calculating the rainfall forecasts for the upcoming 30, 60, and 120 minutes.

The second method utilized these semi-objective forecasts which were modified by the radar meteorologist, if deemed necessary, through use of real-time rain information and knowledge of present weather conditions. These were the forecasts that were transmitted to MSD, and are referred to hereafter as man-machine forecasts.

The individual and accumulated semi-objective forecasts were made to the nearest 0.01 in for each of the three urban areas for 30, 60, and 120 minutes. However, the man-machine forecasts, which were transmitted to MSD by the operator, were given to the nearest 0.1 in but the evaluations of both the semi-objective and man-machine forecasts were made to the nearest 0.01 in.

For the "semi-objective forecasts," rainfall amounts in the urban area were determined solely from the radar-indicated rainfall amounts. Thus, if the radar-indicated amounts were either high or low, the individual and/or accumulated rainfall amounts for forecasts in the next 30, 60, and 120 minutes would also be either high or low when compared to the "ground truth" raingages. However, the "man-machine forecasts" issued by the operator were altered on the basis of the radar-indicated rainfall, the telemetered raingage amounts (when available), and by knowledge of the storm characteristics on the part of the radar meteorologist.

Verification of the forecasts are only shown for the northern and central regions. The forecasts for the southern region were verified, but because the dense raingage network did not completely envelope this area the verification is less reliable than for the north and central. Since the results from the northern and central areas were similar, they have been combined for presentation in this report.

Various types of analyses were made to evaluate the accuracy of the man-machine and semi-objective forecasts. These included 1) determination of the forecast errors in absolute magnitude (inches of rainfall) and percentages for various intensities of 30-, 60-, and 120-minute rainfalls, and for accumulated rainfall amounts during the progress of storms; 2) the frequency of overestimates and underestimates of actual rainfall amounts; 3) differences in forecasting accuracy between June-July and August, when some telemetered, real-time raingage data became available for guidance; and, 4) comparative accuracy of the semi-objective and man-machine forecasts. Similar to the monitoring analyses, results have been summarized in great detail in tables which have been included in Appendix B of this report. In the following paragraphs, only a brief summary of the major findings from the various analyses is presented. The reader is referred to the Appendix for more detailed data and information on each type of analysis performed.

Forecasts of Individual 30- to 120-Minute Amounts

In view of the relatively short sampling period, median forecasting errors are considered the best statistic to provide an overall measure of forecasting accuracy achieved during the demonstration period. These have been used to a large extent to summarize project findings in the ensuing paragraphs. As mentioned earlier, more detailed analyses have been made and are presented in Appendix B of this report.

Table 24 summarizes a comparison between the median forecasting errors for the man-machine and semi-objective techniques. These are shown for intrastorm forecasts of 30-, 60-, and 120-minute rainfall amounts that were transmitted to MSD at 30-minute intervals throughout each storm. The distribution of errors is shown for various classes of forecast amounts (rainfall intensities). Results have been separated into June-July and August time periods, so as to evaluate the effect of the limited real-time raingage data that became available in August to serve as an additional forecasting guide. The number of cases in each forecast category is also indicated in Table 24. The larger number of cases for the semi-objective method in Table 24 is caused by omission of the hydrologically insignificant zero (no rain) forecasts from the summarized statistics. Frequently, when the man-machine forecasts indicated no rain, the radar would indicate small amounts due to light rain aloft that evaporated before reaching the ground, or from the detection of large cloud droplets in non-precipitating clouds.

Table 24 shows a distinct trend for the man-machine forecasts to be superior to the semi-objective technique. For example, during June-July, the man-machine median error for forecasts in the range from 0.30 to 0.99 inch was 16% better (0.21 vs 0.25 in). For 60-minute forecasts, the man-machine error was 11% better (0.29 vs 0.32 in), and for 120-minute forecasts, the improvement was 38% (0.26 vs 0.38 in). The improvement was greatest for the heavier rainfall amounts, those of most interest to the urban hydrologist. The results support our initial concept that substantial improvement in forecasting accuracy could be achieved with a man-machine mix as opposed to purely objective methods, considering the present level of technological development in the radar-rainfall field. The semi-objective forecasts were those calculated by the onsite computer from the radar-rainfall field, and had no man input other than adjustment of the motion and limitations on the rate of growth and intensification, as pointed out earlier. The forecast amounts were strictly objective (machine computed).

The August samples were much smaller than those for June-July. Consequently, a thorough evaluation can not be made of the effect of the August availability of limited telemetered raingage data to the duty meteorologist. Inspection of Table 24 does show a general improvement (smaller median errors) from June-July to August in the man-machine forecasts. However, improvement is also indicated in the semi-objective forecasts which were unaffected by the telemetered raingage data.

Thus, Table 24 suggests that the improvement may only indicate a sampling variation resulting from differences in the type and distribution characteristics of rainfall during the two periods. However, other analyses did indicate that the improvement from June-July to August may have been somewhat better for the man-machine forecasts. Thus, the reduction in large errors appeared slightly greater for the man-machine type, as indicated in Table 25, which shows the percentage of forecasting errors that were less than 50% during the two time periods and for various forecast categories. Again, both types of forecasts show improvement with time in that there tended to be a greater percentage of errors <50% in August, but the changes tended to be somewhat larger for the man-machine type.

Analyses of the percentage of forecast errors exceeding 0.1 in also indicated a greater improvement from June-July to August in suppressing large errors by the man-machine methods (see Appendix B for details). However, at this point the statistical evidence of greater August improvement for the man-machine forecasts certainly can not be considered strong. Actually, large improvement would not be expected, since the primary benefit of the telemetered raingage data in the Water Survey's prediction-monitoring system results from adjustment of the radar-rainfall field. This, in turn, should lead to major improvement in both the semi-objective and man-machine methods.

As expected, Table 24 indicates that the magnitude of the forecasting error increases as forecasts are made for increasingly heavy rainfalls. For example, the median error of 60-minute forecasts for June-July with the man-machine method increased gradually from 0.03 in for predictions of 0.01-0.04 in to 0.29 in for forecasts in the range from 0.30 to 0.99 in. However, the percentage error did not gradually increase with increasing rainfall; in fact, there was a tendency in the man-machine forecasts for it to decrease slightly as the forecast amounts became larger. More detail on the breakdown of both absolute and percentage errors is provided in Appendix B.

Forecasts of Accumulated Rainfall Amounts

Analyses discussed in previous paragraphs were repeated for accumulated rainfall forecasts. Total storm accumulations were predicted at 30-minute intervals for the next 30, 60, and 120 minutes. That is, amounts expected in

Table 24. Comparison of Median Forecasting Errors, Man-Machine vs Semi-Objective Methods, Individual 30- to 120-Minute Amounts, North and Central Stations.

	June-July				August			
Forecast Amount (in)	N		Error (in)		N		Error (in)	
	MM	SO	MM	SO	MM	SO	MM	SO
30-Minute Forecasting Errors								
0.01-0.04	6	57	0.02	0.03	0	27	--	0.03
0.05-0.09	9	15	0.04	0.04	1	14	--	0.03
0.10-0.19	36	13	0.07	0.08	29	15	0.04	0.07
0.20-0.29	19	9	0.15	0.17	9	9	0.16	0.10
0.30-0.99	9	8	0.21	0.25	2	5	--	0.17
60-Minute Forecasting Errors								
0.01-0.04	6	57	0.03	0.03	0	31	--	0.03
0.05-0.09	7	22	0.03	0.05	1	10	--	0.03
0.10-0.19	38	19	0.08	0.10	28	15	0.07	0.08
0.20-0.29	15	5	0.10	0.18	17	13	0.08	0.10
0.30-0.99	28	21	0.29	0.32	11	16	0.18	0.26
≥1.00	1	2	--	--	0	0	--	--
120-Minute Forecasting Errors								
0.01-0.04	9	51	0.02	0.03	2	20	--	0.03
0.05-0.09	8	28	0.06	0.07	1	15	--	0.05
0.10-0.19	50	19	0.07	0.08	34	16	0.07	0.09
0.20-0.29	13	15	0.16	0.14	12	13	0.12	0.10
0.30-0.99	41	28	0.26	0.38	22	21	0.09	0.22
≥1.00	5	6	0.65	0.76	0	3	--	--

N = Number of Cases
MM = Man-Machine
SO = Semi-Objective

Table 25. Percent of Semi-Objective and Man-Machine Forecasts with <50% Error in North and Central Sections during June-July and August.

Forecast Amount (in)	Man-Machine June-July N	Man-Machine June-July %	Man-Machine August N	Man-Machine August %	Objective June-July N	Objective June-July %	Objective August N	Objective August %
				30-Minute Forecasts				
0.01-0.19	36	22	29	48	13	23	15	33
0.20-0.29	19	26	9	22	9	33	9	56
0.30-0.99	9	11	2	0	8	13	5	40
				60-Minute Forecasts				
0.10-0.19	38	16	28	32	19	37	15	40
0.20-0.29	15	20	17	47	5	20	13	31
0.30-0.99	28	21	11	46	21	19	16	31
				120-Minute Forecasts				
0.10-0.19	50	32	34	32	19	32	16	38
0.20-0.29	13	15	12	58	15	33	31	54
0.30-0.99	41	37	22	77	28	21	21	48

these upcoming periods were added to the calculated rainfall totals up to the time of the latest forecast. Results are presented in Table 26.

Table 26 shows a pronounced trend for the man-machine forecasts to be more accurate than the semi-objective predictions. In general, this is evident for all forecasting categories and time periods.

However, there is a substantially stronger trend for an improvement in man-machine forecasts from June-July to August than was apparent for the individual 30- to 120-minute forecasts in Table 26. For example, in the accumulative forecasts fro 60 minutes in advance, the improvement in the median error increased from 0.02 in (0.08 to 0.06 in) for forecasts of 0.10 to 0.19 in to 0.60 inch (0.81 vs 0.21 in) for peedictions in the range from 1.00 to 1.49 in. Furthermore, the man-machine improvement was substantially greater than the semi-objective change which was erratic with respect to forecast amount and forecast period, and was only slight overall. Thus, the accumulative analyses provide some solid support for an improvement in the man-machine forecasts with only limited telemetered gage data available to help adjust the machine forecasts.

Similar to the individual period forecasts, the absolute error increased with increasing rainfall, but the percentages error did not change much and tended to decrease slightly with the heavier predicted amounts. In general, the analyses of accumulative rainfall forecasts provide strong support for findings discussed earlier concerning forecasts of individual 30-, 60-, and 120-minute rainfall amounts.

Table 26. Comparison of <u>Median</u> Forecasting Errors, Man-Machine vs Semi-Objective Methods, <u>Accumulative</u> Intrastorm Amounts, North and Central Sections.

	June-July				August			
Forecast Amount (in)	N		Error (in)		N		Error (in)	
	MM	SO	MM	SO	MM	SO	MM	SO
				30-Minute Forecasting Errors				
0.01-0.04	1	125	--	0.02	0	28	--	0.03
0.05-0.09	4	73	0.07	0.07	0	24	--	0.07
0.10-0.19	90	43	0.08	0.13	22	19	0.05	0.13
0.20-0.29	36	39	0.05	0.17	22	25	0.09	0.16
0.30-0.49	40	46	0.15	0.19	15	10	0.04	0.30
0.50-0.74	41	47	0.29	0.36	46	17	0.10	0.36
0.75-0.99	28	26	0.43	0.39	3	27	0.38	0.54
1.00-1.49	56	56	0.78	0.84	24	25	0.21	0.68
≥1.50	16	20	0.92	1.18	0	25	--	0.80
				60-Minute Forecasting Errors				
0.01-0.04	0	116	--	0.03	0	23	--	0.03
0.05-0.09	4	65	0.04	0.07	0	20	--	0.07
0.10-0.19	87	42	0.08	0.14	19	17	0.06	0.16
0.20-0.29	33	38	0.09	0.17	21	21	0.09	0.17
0.30-0.49	36	40	0.15	0.18	17	12	0.08	0.34
0.50-0.74	38	42	0.28	0.37	39	18	0.12	0.36
0.75-0.99	28	26	0.56	0.49	9	27	0.18	0.53
1.00-1.49	56	57	0.81	0.83	22	25	0.21	0.68
≥1.50	14	18	1.12	1.17	0	25	--	0.75
				120-Minute Forecasting Errors				
0.01-0.04	4	88	0.00	0.03	2	15	--	0.03
0.05-0.09	4	60	0.08	0.08	0	15	--	0.08
0.10-0.19	84	42	0.08	0.14	19	13	0.06	0.10
0.20-0.29	29	34	0.04	0.16	14	15	0.12	0.19
0.30-0.49	32	31	0.14	0.18	17	13	0.08	0.31
0.50-0.74	30	37	0.48	0.41	34	17	0.10	0.43
0.75-0.99	20	21	0.65	0.68	10	25	0.18	0.42
1.00-1.49	51	55	0.75	0.87	19	15	0.21	0.46
≥1.50	14	15	1.20	1.19	0	25	--	0.49

N = Number of Cases
MM = Man-Machine
SO = Semi-Objective

SECTION 7

SUMMARY AND RECOMMENDATIONS

Summary

CHAP entailed a comprehensive 4-year research project whose major purposes were to expand the use of meteorological information 1) in the design of urban storm and sanitary systems and 2) in the real-time operation of urban hydrologic systems, so as to improve protection of people, property, and the environment during potential flash flood situations. This report has been concerned with the second of the above two broad objectives.

Carrying out this objective involved the development of a real-time, prediction-monitoring system utilizing a combination of weather radar and telemetered recording raingage data. Monitoring of rainfall from heavy storms approaching and crossing the urban area and predicting the rainfall distribution over the urban area for the upcoming 30-, 60-, and 120-minutes were the two basic goals of this research. This information would then provide a major contribution to optimizing the operation of urban hydrologic systems in potentially dangerous weather conditions.

During the first 2.5 years, data were gathered through use of a sophisticated 10-cm radar system and a dense network of 317 recording raingages on an area of approximately 4500 mi^2 in and around the Chicago urban area in northeastern Illinois. These data were basic to development of the prediction-monitoring techniques carried out concurrently during this 2.5-year period. Results were successful, so a real-time operational project was carried out from 18 June to 15 August 1979 to demonstrate the system and its benefits for potential users of the prediction-monitoring system.

The present system involves use of a man-machine combination in which the duty meteorologist has the perogative of adjusting the monitoring and prediction outputs generated by the onsite computer from the rainfall field as viewed by the radar-raingage system. For various reasons, this was considered necessary at the present stage of technological development in optimizing the application of radar to real-time quantitative measurement and short-period prediction of heavy storm rainfall events.

An initial key to evaluating the developed system is how dependable it is in routine operation. During the demonstration period, 99% of the possible transmissions to MSD during storms were made. Only a very few transmissions were missed and these because of routine maintenance, minor equipment problems, or outages due to lightning strikes.

During the demonstration period, the rain monitoring accuracy with the man-machine combination was definitely superior to that obtained with unadjusted radar measurements, and was equivalent, if not slightly superior, to the measurements made by the relatively dense network of raingages (approximately 6-mi spacing) operated by MSD in the urban area. Further, the man-machine combination was not operating at full effectiveness because of lack of telemetered raingage data for guidance in adjustment of the radar-indicated rainfall field. When limited telemetered raingage data became available in August, definite improvement in the accuracy of monitored rain amounts occurred, and this improvement was most pronounced in the heavier rainfall, which are of primary interest to the urban hydrologist. Experience during and prior to the demonstration period has shown that the man-machine combination can provide real-time information on the rainfall distribution in time and space which is sufficiently accurate to be of major assistance to the urban hydrologist in operating his systems.

Evaluation of the forecasting success with the man-machine combination also provided strong support for the applicability of the prediction-monitoring system to real-time operational problems in urban areas. The man-machine combination was proven definitely superior to radar alone in providing short-term forecasts of 30 to 120 minutes. With the addition of some telemetered raingage data in August, the man-machine combination improved substantially in accuracy. The man-machine combination also demonstrated the potential for developing highly accurate heavy rain forecasts for Chicago for periods of 2 to 6 hours in advance; hence, complimenting the radar approach used for 30 to 120 minutes. This strongly supports our original project concept that this method can provide very useful input to real-time operation of urban hydrologic systems.

Both monitoring and prediction information proved useful to MSD during the demonstration period. Accuracy levels were achieved that are sufficient to facilitate and improve the operational efficiency of urban systems. Further improvement in both monitoring and prediction accuracy can be expected when the system operates at full effectiveness; that is, with telemetered raingage input to the radar system for adjusting the radar-indicated rainfall field.

Recommendations

Further operation of the prediction-monitoring system in conjunction with user operations is most desirable. The 1979 demonstration period was too short to evaluate completely the system under all types of storm situations, and the data sample was not large enough to define the accuracy of the monitoring and prediction with a high degree of statistical reliability. However, the greatest need is for more operations with the system at full effectiveness; that is, with telemetered raingage data routinely transmitted and integrated into the computer computations of the radar-indicated rainfall field.

Satellite cloud data (not available in the CHAP tests) would be a useful addition to the prediction system to serve as a guide in alerting operational personnel on the expected characteristics of incoming, large-scale storm systems. Such information would help in estimating size, intensity, and movement of such storm systems many hours in advance of their arrival in the urban area.

SECTION 8

USER INTERACTIONS

A vital part of the CHAP project, and its final year of field demonstration and evaluation related to the transfer of information about radar-rainfall measurement systems and other project results to the user community. The major user community is defined as the operational and design elements of large metropolitan areas who are concerned with runoff and water quality. However, there are also important users in the scientific and technical communities.

Goals

The general goals of the information-to-user effort in this 1-year project and the entire CHAP were two-fold.

The first goal was to transfer information from CHAP about radar-raingage measurement systems to users across the nation. This was to be accomplished largely by published papers in a variety of user journals and by talks at national meetings.

The second and equally important goal was related to the actual technology transfer to real users. In particular, we have long hoped that an outcome of the project in the Chicago area would consist of the user taking on the costs and responsibility of the radar forecast system, either as a longer demonstration effort or as an ongoing, long-term effort. Such an action would demonstrate to the world the project's work and the application of the developed system as an operating system for consideration by other cities. It should be realized that the 2 month demonstration project in 1979 was not long enough to demonstrate fully all the applications to various potential users in addition to the MSD operational users.,

We believe that a longer demonstration will lead to the involvement of other possible users (NIPC, the City of Chicago, and U. S. Corps of Engineers) who will grow to appreciate the system's utility and the benefits to their particular areas of responsibility. For example, there are needs in the winter for snow measurement relating to the City of Chicago and its snow clearance operations. The U. S. Corps of Engineers has the responsibility for sustaining the flow in the Illinois River system below Chicago for barge traffic. Of course, MSDGC is responsible for the water quality and runoff flooding problems of Chicago. Hence, there are many potential users who could support a permanent operation, should that come to pass. A major goal of our interactions with MSD and other groups in the Chicago area during this project was to create project awareness and to secure interest about future support of a longer project.

Workshops and Meetings with Users

To help the user and expedite information transferral aspects of this project, an 8-person advisory board was established in 1976 (see Table 27). The

Table 27. User Advisory Panelists for CHAP.

Robert Clark, Associate Director or Hydrology, National Weather Service, NOAA, Silver Spring, Maryland.

Harold Coffee, Chief Engineer, Department of Public Works, San Francisco, California.

Clint Keifer, President, Keifer and Associates, Chicago.

Ray K. Linsley, President, Hydrocomp, Inc., Palo Alto, California.

Murray B. McPherson, Director, ASCE Urban Water Resources Research Program, Marbelhead, Massachusetts.

Forrest C. Neil, Chief Engineer, Metropolitan Sanitary District, Chicago.

Dick Pavia, Commissioner, Department of Waters and Sewers, Bureau of Engineering, City of Chicago.

Joseph A. Smedlie, Chief Engineer, Northeastern Illinois Planning Commission, Chicago.

board included four engineers from the Chicago area. These four members of the advisory board (the others are from distant locales) were invited to the radar site for a briefing on July 31, 1979. The four Chicago area people attended this 1-day site and rational inspection. Very constructive discussions were held relating to the 2-month demonstration effort, and follow-on alternatives. It is worth noting that this advisory board visit and a second larger user workshop were conducted using State (Water Survey) funds with some help from the Urban Water Resources Program of ASCE, and were not based on NSP funds. The project had proposed funding for these to NSF, who declined to fund such user interactive activities.

The second and more extensive effort of information transfer was conducted on August 13, 1979. This was planned with the considerable assistance of Dr. M. B. McPherson, Director of the ASCE Urban Water Resources Research Program. Dr. McPherson is one of the four other (non Chicago) advisory members to the CHAP project. As a result of our discussions with Dr. McPherson in June, he issued a memorandum of invitation to some 40 urban engineering offices around the nation, inviting them to attend the one-day, information-instructional period at the radar site, to be given by Water Survey project personnel.

After the invitational announcement, the Water Survey took the lead in organizing all facets of the workshop. Rooms were secured at a motel near O'Hare Airport. Most out-of-state visitors flew into Chicago on 12 August. The Survey sent three vehicles to transport the 15 visitors to the radar site early on the 13th. A 1.5-hour briefing was conducted for these 15 and 11 other guests including staff of MSD, the U. S. Corps of Engineers (Chicago), the U. S. EPA (Chicago), the Illinois Division of Water Resources (Springfield), and two Chicago-area private engineering firms. The total visitor attendance was 29. Engineers and hydrologists came from Detroit, Montreal, Boston, San Antonio, San Francisco, Denver, St. Louis, and other cities. Some cities sent representatives from private firms. The group was very interested in the workshop.

At the formal briefing, we described the overall goals of CHAP and its dimensions over its four year history. We then described how the radar-raingage system worked and provided some maps to illustrate the start of a typical heavy rain event on July 30th and how we monitored and forecasted the rain. After several questions of sufficient complexity to show interest, the group began a tour of the radar site. The group was then divided into four subgroups, and we conducted a rotating tour with 15- to 20-minute presentations at four project activity areas. Don Staggs gave briefings on the radar hardware system; John Vogel and Dave Brunkow discussed the radar output-forecasting integration system; Doug Green described the weather forecast system; and Stan Changnon summarized the general aspects of the program and potential systems for other locales.

After this 2-hour tour and briefing, a period of open and extensive questioning was conducted. Everyone seemed most concerned about two topics: 1) what kind of system should a given city have and what would it cost, and 2) from those in the Chicago area, how we might go about securing support for a further demonstration project? Most everyone believed that a longer demonstration effort was needed, primarily to interest, instruct, inform, and educate all the users, and also to test the system's capability in rain and snow during the cold season.

At the briefing, we also described the two reports that we intended to issue at the conclusion of CHAP. One of these reports would describe and evaluate the 2-month operational effort, the user interaction, and serve as the "final report." It was recommended to us that it should concentrate 1) on the statistical accuracy of the rain forecasts (under different weather conditions and day-night situations), and 2) on the accuracy of the monitoring of rain amounts over the city. Reasons for failures, either technological or meteorological (in forecasting), should be examined.

The second document that we discussed, in keeping with the information and technology transfer to users, was the "user's manual." This guidebook, with their concurrence, should address the issue as to what radar-raingage mixes would be recommended for different kinds of cities, the type of computers and software to be used, etc. Those attending the meeting indicated extreme interest in obtaining the user's manual. We asked several of them to review the draft of this document and they agreed to do so. The day-long workshop was concluded at 4 p.m., and the attendees were returned to O'Hare Airport.

The workshop was extremely beneficial to CHAP and presumably to the visitors. We had a large audience, and extreme interest in the program was exhibited.

Examples of other types of meetings with users during 1979 are presented in Table 28. Close liasion was kept with the prime user, MSD, and its operational staff and program decision makers.

Talks and Papers

Two other major means of communication with users include talks at a variety of scientific and engineering meetings, and papers written and published in journals of various societies.

Table 29 presents a list of the talks given about CHAP since the project began in 1976. Those relating to the last 1-year NSF funded phase of the project appear toward the end of the table.

Table 30 lists the publications to date resulting from CHAP. Four other papers are in preparation and will be submitted for publication in various journals in 1980.

Table 28. Examples of Other Interactions with Local-Regional Users in 1979.

Briefing for 15 staff members of the Metropolitan Sanitary District (MSD) in Chicago during May.

Three 1-day observational visits at MSD to view actual system operations to interact with users in June, July, and August.

Meeting with new operational staff members of MSDGC at their offices in June 1979.

Meeting with senior representatives of MSDGC and Illinois Division of Water Resources in Chicago in September to discuss follow-on project.

Table 29. Oral Presentations Concerning CHAP, 1976-1980.

"The Chicago Hydrometeoroiogical Program," given by r. A. Kuff, Annual Meeting of American Geophysical Union, Washington, DC, March 1976.

"A Hydrometeorologic System for Urban Applications," given by S. A. Changnon, National Conference on Hydrometeorology of American Meteorological Society, Ft. Worth, TX, April 1976.

"Heavy Rainfall Relations in a Major Metropolitan Area," given by J. Vogel, National Conference on Hydrometeorology of American Meteorological Society, Ft. Worth, TX, April 1976.

"The Urban Hydrometeorology Project of Chicago," given by F. A. Huff, Seminar of Chicago Chapter of AMS, University of Chicago, March 1976.

"The Chicago Area Project - A New Urban Study," given by S. A. Changnon, Lecture, Western Michigan University, Kalamazoo, May 1976.

"Research Opportunities on CAP," given by S. A. Changnon, talk, Michigan University, East Lansing, May 1976.

"Chicago Area Research Related to Lake Michigan," given by S. A. Changnon, staff seminar, University of Michigan and Great Lakes Environmental Research Center, Ann Arbor, MI, October 1976.

"The Chicago Area Rainfall Project," given by W. C. Ackermann, American Water Resources Association Conference, Chicago, March 1976.

"Heavy Rainfall Relations Over Chicago and Northeastern Illinois," given by J. Vogel, 12th American Water Resources Association Conference, Chicago, September 1976.

"Hydrometeoroiogicai Research Program in Urban Hydrology Applications," given by F. A. Huff, 12th American Water Resources Conference, Chicago, September 1976.

"A Review of the Chicago Hydrometeoroiogicai Project," a series of talks given by W. C. Ackermann, S. A. Changnon, and F. A. Huff, Chicago Advisory Panel, Chicago, October 1976.

"Heavy Rainstorms in Urban Area," given by F. A. Huff, International Symposium on Urban Hydrology, Amsterdam, October 1977.

"Impacts of Chicago Hydrometeoroiogicai Area Project on Hydrologists and Design," given by S. A. Changnon, Meeting of Illinois Section of ASCE, Chicago, April 1977.

"Time and Space Distribution Models for Urban Rainstorms," given by J. L. Vogel, Conference on Hydrometeorology, Toronto, October 1977.

Table 29 (continued).

"Radar Echo Characteristics Associated with Intense Rainfall Rates in the Chicago Area," given by N. G. Towery, Conference on Hydrometeorology, Toronto, October 1977.

"Hydrometeorological Characteristics of Severe Rainstorms in Chicago Metropolitan Area," given by N. G. Towery, Conference on Hydrometeorology, Toronto, October 1977.

"Using Rainfall Data in Urban Hydrolbgic Applications," given by F. A. Huff, Conference on Water Quality Surveys for 208 Projects, April 1977.

"Meteorological Aspects of a Severe Urban-Centered Rainstorm," given by S. A. Changnon, Conference on Flash Floods: Hydrometeorological Aspects, Los Angeles, May 1978.

"A Local Severe Rainstorm," given by R. C. Grosh, Conference on Flash Floods Hydrometeorological Aspects, Los Angeles, May 1978.

"Real-Time Monitoring and Prediction for Urban Hydrologic Operations Utilizing A Radar-Raingage-Onsite Computer System," given by J. L. Vogel at Symposium on Digital Radar Reflectivity Processing with Application to Hydrometeorology, Edmonton, Canada, October 1979.

"Convective Rain Monitoring and Forecasting System for an Urban Area," given by J. L. Vogel, 19th Conference on Radar Meteorology, Miami, April 1980.

"Urban Heavy Rain Forecasting System," given by F. A. Huff, Conference on Flash Floods, Atlanta, GA, March 1980.

"Quantitative Rainfall Monitoring and Forecasting for an Urban Area," to be given by J. L. Vogel, International Symposium on Urban Storm Runoff, Lexington, KY, July 1980.

"Urban Rainfall Prediction System," to be given by S. A. Changnon, ASCE Hydraulics Conference, Chicago, August 1980.

"Real-Time Measurements of Convective Precipitation over an Urban Region," to be given by J. L. Vogel, International Symposium on Hydrological Forecasting, Oxford, April 1980.

"A Digitial Radar-Based Rainfall Forecasting and Monitoring Tool," given by J. L. Vogel, 19th Conference on Radar Meteorology, Miami, April 1980.

Table 30. CHAP Publications.

Ackermann. W. C., 1975: "The Future of Water Resources in Northeastern Illinois." Journal American Water Works Association, December, 691-694.

Changnon, S. A., 1978: Windy City Weather Effects. Science News, 114(15), 264.

Changnon, S. A., 1978: "The Meteorological Aspects of a Severe Urban-Centered Rainstorm. Preprints, Conference on Flash Floods, Amer. Meteor. Soc, Boston, 152-157.

Changnon, S. A., 1978: "Heavy Falls of Hail and Rain Leading to Roof Collapse." Journal of Structural Division ASCE, Vol. 104, No. ST1, 198-200.

Changnon, S. A., F. A. Huff, N. G. Towery, and J. L. Vogel, 1978: CHAP: A Comprehensive New Study of Urban Hydrometeorology. Final Report NSF Grant ENV76-01447, Illinois State Water Survey, Urbana, 51 pp.

Changnon, S. A. and R. G. Semonin, 1978: "Chicago Area Program: A Major New Atmospheric Effort." Bulletin Amer. Meteor. Soc, 59, 153-160.

Changnon, S. A. and F. A. Huff, 1976: "Multi-Purpose Hydrometeorologic System for Urban Hydrology." Preprints Conference on Hydrometeorology, Amer. Meteor. Soc, Boston, 42-47.

Changnon, S. A. and F. A. Huff, 1976: Chicago Hydrometeorological Area Project: A Comprehensive New Study of Urban Hydrometeorology. First Interim Report, NSF/RANN Grant ENV76-01447, 69 pp.

Dettwiller, J. and S. A. Changnon, 1975: "Possible Urban Effects on Maximum Daily Rainfall at Paris, St. Louis, and Chicago." Journal of Applied Meteorology, Vol. 15, 517-519.

Fujita, T. T., M. R. Hjelmfelt, and S. A. Changnon, 1977: Mesoanalysis of Record Chicago Rainstorms Using Radar, Satellite, and Raingage Data. Preprints 10th Conference on Severe Storms. Amer. Meteor. Soc, Boston, 65-72.

Grosh, R. C., 1978: "A Local Severe Rainstorm." Preprints Conference on Flash Floods, Amer. Meteor. Soc, Boston, 10 pp.

Huff, F. A., 1977: Effects of the Urban Environment on Heavy Rainfall Distribution. Water Resources Bulletin, Vol. 13, No. 4, 807-816.

Huff, F. A., 1977: Sampling, Analysis, and Interpretation of Rainfall for Hydrologic Applications. Proc. Workshop on 208 Water Quality Surveys, Assoc. Metro. Sewage Agencies, Washington, DC, J3-J13.

Table 30 (continued).

Huff, F. A., and S. A. Changnon, 1977: A Hydrometeorological Research Program. Water Resources Bulletin, 13, 573-581.

Huff, F. A., and N. G. Towery, 1977: Hydrometeorological Characteristics of Severe Rainstorms in Chicago Metropolitan Area. Preprints, Second Conference on Hydrometeorology, Amer. Meteoro. Soc., Boston, 214-219.

Huff, F. A., and J. L. Vogel, 1976: Hydrometeorology of Heavy Rainstorms in Chicago and Northeastern Illinois, Phase 1-Historical Studies. Report of Investigation 82, Illinois State Water Survey, Urbana, 63 pp.

Towery, N. G., and F. A. Huff, 1977: Radar Echo Characteristics Associated with Intense Rainfall Rates in the Chicago Area. Preprints, Second Conference on Hydrometeorology, Amer. Meteor. Soc, Boston, 286-289.

Vogel, J. L., 1976: Heavy Rainfall Relations in a Major Metropolitan Area. Preprints, Conference on Hydrometeorology, Amer. Meteor. Soc, Boston, 86-91.

Vogel, J. L., and F. A. Huff, 1977: Heavy rainfall relations over Chicago and northeastern Illinois. Water Resources Bulletin, Vol. 13, No. 5, 959-971.

Closely Related Reports of Other Water Survey Research and Staff

Gatz, D. F., and S. A. Changnon, 1976: Atmospheric Environment of the Lake Michigan Region. Vol. 8. ANL/ES-40, Argonne, Illinois, 164 pp.

Wenzel, H. G., Jr., and M. L. Terstriep, 1976: Sensitivity of Selected ILLUDAS Parameters. Illinois State Water Survey Contract Report 178, Urbana, 25 pp.

Terstriep, M. L., M. L. Voorhees, and G. M. Bender, 1976: Conventional Urbanization and its Effects on Storm Runoff. Illinois State Water Survey, 68 pp.

REFERENCES

Atlas, D., 1964: Advances in radar meteorology, in Advances in Geophysics, 10, Edited by H. E. Landsberg and J. Van Mieghem, Academic Press, New York, NY, 317-478.

Barnes, S. L., 1964: A technique for maximizing details in numerical weather map analysis. J. Appl. Meteor., 3, 396-409.

Brandes, E. A., 1975: Optimizing rainfall estimates with the aid of radar. J. Appl. Meteor., 14, 1339-1345.

_____, 1974: Radar rainfall pattern optimizing technique. NOAA Tech. Memo. ERL NSSL-67, 16 pp.

Byers, H. R., 1948: The use of radar in determining the amount of rain falling over a small area. Trans. Amer. Geophys. Union, 29, 187-196.

Cain, D. E., and P. L. Smith, 1977: A sequential analysis strategy for adjusting radar rainfall estimates on the basis of raingage data in real-time. Preprints, Second Conf. on Hydrometeorology, Amer. Meteor. Soc., Boston, MA, 280-285.

_____, and_____, 1976: Operational adjustment of radar estimated rainfall with raingage data in real-time. Preprints 17th Conf. on Radar Meteor., Amer. Meteor. Soc., Boston, MA, 553-558.

Changnon, S. A., 1978a: The meteorological aspects of a severe urban-centered rainstorm. Preprints, Conf. on Flash Floods, Amer. Meteor. Soc, Boston, MA, 152-157.

_____, 1978b: Heavy falls of hail and rain leasing to roof collapse. J. of Structural Division ASCE, Vol. 4, No. ST1, 198-200.

_____, and F. A. Huff, 1976: Multi-purpose hydrometeorologic system for urban hydrology. Preprints Conf. on Hydrometeorology, Amer. Meteor. Soc., Boston, MA, 42-47.

_____, and R. G. Semonin, 1978: Chicago area program. A Major New Atmospheric Effort. Bull. Amer. Meteor. Soc., 59, 153-160.

Harrold, T. N., E. J. English, and C. A. Nicholass, 1974: The accuracy of radar derived rainfall measurements in hilly terrain, Quart. J. R. Meteor. Soc., 100, 331-350.

Hildebrand, P. H., N. Towery, M. R. Snell, 1979: Measurement of convective mean rainfall over small areas using high-density raingages and radar. J. Appl. Meteor., 18, 1316-1326.

Huff, F. A., 1967: The adjustment of radar estimates of storm mean rainfall with raingage data. J. Appl. Meteor., 6, 52-56.

_____, and S. A. Changnon, 1977: A hydrometeorological research program. Water Res. Bull., 13, 573-581.

_____,_____, N. G. Towery, and J. L. Vogel, 1978: Chicago Hydrometeorological Area Project: A Comprehensive New Study of Urban Hydrometeorology. Final Report on NSF ENV76-01447, Illinois State Water Survey, Urbana, IL, 51 pp.

_____, J. C. Neill, M. Spock, Jr., 1956: Evaluation of a low-powered 3-cm radar for quantitative rainfall measurements. Meteor. Research Rept. No. 4, Illinois State Water Survey, Urbana, IL, 35 pp.

_____, and N. G. Towery, 1977: Hydrometeorological characteristics of severe rainstorms in Chicago metropolitan area. Preprints, Second Conf. on Hydrometeorology, Amer. Meteor. Soc., Boston, MA, 214-219.

_____, and J. L. Vogel, 1976: Hydrometeorology of Heavy Rainstorms in Chicago and Northeastern Illinois, Phase 1-Historical Studies. Report of Invest. 82, Illinois State Water Survey, Urbana, 63 pp.

Jones, D. M. A., 1956: Rainfall drop-size distribution and radar reflectivity. Meteor. Research Rept. No. 6, Illinois State Water Survey, Urbana, IL, 20 pp.

Marshall, J. S., and W. M. Palmer, 1948: The distribution of raindrops with size. J. Meteor., 5, 165-166.

Pavia, R. A., 1979: Chicago water system: Opportunities and challenges of Lake Michigan. J. of the Water Resources Planning and Management Division, Proceeding of the Amer. Soc. of Civil Engineering, 105, No. WR2, 371-375.

Simpson, J., N. Westcott, R. Clerman, and R. Pielke, 1978: On Cumulus Mergers. Final Report, NSF Grant DES 75-039484, Dept. of Environmental Sciences, University of Virginia.

Stout, G. E., and E. A. Mueller, 1968: Survey of relationships between rainfall rate and radar reflectivity in the measurement of precipitation. J. Appl. Meteor., 7, 465-474.

Towery, N. G., and F. A. Huff, 1977: Radar echo characteristics associated with Intense rainfall rates in the Chicago area. Preprints, Second Conf. on Hydrometeorology, Amer. Meteor. Soc., Boston, MA, 286-289.

U. S. Supreme Court, 1967: Wisconsin, et al., vs. Illinois, et al., United States Report, 388, 426.

Vogel, J. L., 1976: Heavy rainfall relations in a major metropolitan area. Preprints, Conf. on Hydrometeorology, Amer. Meteor. Soc, Boston, MA, 86-91.

Vogel, J. L., and F. A. Huff, 1977: Heavy rainfall relations over Chicago and northeastern Illinois. *Water Res. Bull.*, *13*, No. 5, 959-971.

Wexler, R., 1947: Radar detection of a frontal storm 18 June 1946, *J. Meteor.*, *4*, 38-44.

Wiiggert, V., S. S. Ostlund, G. J. Lockett, and J. V. Stewart, 1976: *Computer Software for the Assessment of Growth Histories of Weather Radar Echoes*. NOAA Tech. Memo. ERL WMPO-35, Boulder, 86 pp.

Wilson, J. W., 1976: Radar-raingage precipitation measurements - A summary. *Preprints, First Conf. on Hydrometeorology*, Amer. Meteor. Soc., Boston, 72-75.

_____, 1970: Integration of radar and gage data for improved rainfall measurements. *J. Appl. Meteor.*, 9, 489-497.

_____, and E. A. Brandes, 1974: Radar measurement of rainfall - A summary, *Bull. Amer. Meteor. Soc.*, *60*, 1048.

Woodley, W. L., and A. Herndon, 1970: A raingage evaluation of the Miami reflectivity rainfall rate relation. *J. Appl. Meteor.*, 9, 242-257.

_____, A. R. Olsen, A. Herndon, and V. Wiggert, 1975: Comparison of gage and radar methods of convective rain measurement, *J. Appl. Meteor.*, *14*, 909-928.

_____, _____, _____, and _____, 1974: *Optimizing the Measurement of Convective Rainfall in Florida*. Tech. Memo. ERL'WMPO-18, Coral Gables, FL, 99 pp.

Zawadski, I. I., 1975: On radar-raingage comparison. *J. Appl. Meteor.*, *14*, 1430-1436.

APPENDIX A

DETAILED ANALYSES OF RAINSTORM MONITORING DURING 1979

Tables Al to A30 provide detailed information on the distribution of measurement errors in the monitoring of 30-minute rainfall amounts. The standard of comparison is the dense raingage network (Fig. 4) operated by the Water Survey in the Chicago urban area during the 1979 demonstration period, 18 June to 15 August. This network had a gage spacing of approximately 3 miles, a distance previous research had shown to provide accurate measurements of areal mean rainfall.

Measurement errors were determined for 1) the MSD network of telemetered raingages, with an average spacing of 6 miles (Tables Al to A4), 2) the man-machine combination, in which the duty meteorologist had the prerogative of adjusting radar-indicated rainfall amounts through use of available synoptic information on the storm characteristics and knowledge accumulated from previous work on rainfall distributions and radar interpretation (Tables A5 to A8), and 3) unadjusted radar-rainfall estimates made with the radar system situated at the Joliet field site (Tables A9 to Al2). Tables A13 to A15 present comparisons between the three sets of measurements. Analyses were performed separately for June-July and August, because limited telemetered raingage data became available in August for use-as a guide by the duty meteorologist in the man-machine monitoring. Furthermore, measurement errors have been classified as to whether they were underestimates or overestimates. Errors have been defined in inches of rainfall and percentages.

Tables A16 to A30 are analogous to the 30-minute tables, but are based on monitoring of accumulative rainfall amounts throughout each storm during the demonstration period.

No text is included with this Appendix since the tables are considered self-explanatory, and interpretation is left to the judgment of the reader.

Table A1. Frequency of errors in 30-minute rainfall measurements by MST) network in north and central during June-July.

MSD 30-minute amounts (inch)

Error (inch)	0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.99	TOTAL
-0.50 to -0.99	0	1	0	0	0	0	1
-0.25 to -0.49	0	0	0	0	0	0	0
-0.11 to -0.24	2	1	0	3	0	0	6
-0.05 to -0.10	6	0	1	1	2	2	12
-0.01 to -0.04	29	22	7	1	1	0	60
0.0	299	24	4	0	0	0	327
0.01 to 0.04		44	10	2	0	1	57
0.05 to 0.10		0	8	6	0	0	14
0.11 to 0.24		0	0	1	1	0	2
0.25 to 0.49		0	0	0	1	0	1
TOTAL	336	92	30	14	5	3	480

Table A2. Frequency of errors in 30-minute rainfall measurements by MSD network in north and central during August.

	MSD 30-minute amounts (inch)						
Error (inch)	0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.99	TOTAL
-0.25 to -0.49	0	0	0	0	1	0	1
-0.11 to -0.24	0	1	0	3	0	1	5
-0.05 to -0.10	2	2	2	2	0	1	9
-0.01 to -0.04	17	15	12	5	1	0	50
0.0	131	8	4	2	0	0	145
0.01 to 0.04	0	8	4	5	0	0	17
0.05 to 0.10	0	0	1	0	1	0	2
0.11 to 0.24	0	0	0	0	0	1	1
TOTAL	150	34	23	17	3	3	230

Table A3. Frequency of percent error in 30-minute rainfall measurements by MSD network in north and central during June-July.

MSD 30-minute amounts (inch)

Percent error	0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.99	TOTAL
-100	37	0	0	0	0	0	37
-70 to -99		6	0	0	0	0	6
-50 to -69		12	0	2	0	0	14
-20 to -49		5	6	3	2	1	17
-1 to -19		0	2	0	1	1	4
0	299	24	4	0	0	0	327
1 to 19		0	1	1	0	1	3
20 to 49		1	1	0	0	0	2
50 to 99		5	5	6	0	0	16
100 to 199		11	3	1	0	0	15
200 to 499		1	3	0	1	0	5
≥ 500		0	3	0	0	0	3
∞		27	2	1	1	0	31
TOTAL	336	92	30	14	5	3	480

Table A4. Frequency of percent error in 30-minute rainfall measurements by MSD network in north and central during August.

	MSD 30-minute amounts (inch)						
Percent error	0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.99	TOTAL
-100	19	0	0	0	0	0	19
-70 to -99		3	0	0	0	0	3
-50 to -69		11	2	1	1	0	15
-20 to -49		4	6	5	0	1	16
-1 to -19		0	6	4	1	1	12
0	131	8	4	2	0	0	145
1 to 19		0	2	1	0	0	3
20 to 49		0	1	4	1	0	6
50 to 99		0	1	0	0	0	1
100 to 199		4	0	0	0	1	5
200 to 499		0	0	0	0	0	0
≥ 500		0	0	0	0	0	0
∞		4	1	0	0	0	5
TOTAL	150	34	23	17	3	3	230

Table A5. Frequency of errors in 30-minute man-machine rainfall in north and central during June-July.

Error (inch)	Man-Machine 30-minute amounts (inch)						
	0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.99	TOTAL
-0.50 to -0.99	0	0	0	1	0	0	1
-0.25 to -0.49	0	0	0	0	0	0	0
-0.11 to -0.24	1	0	0	1	1	0	3
-0.05 to -0.10	70	0	2	0	0	3	75
-0.01 to -0.04	316	0	8	12	2	0	338
0.05 to 0.10		0	3	34	6	0	43
0.11 to 0.24		0	0	0	7	7	14
0.25 to 0.49		0	0	0	0	3	3
0.50 to 0.99		0	0	0	0	1	1
TOTAL	387	0	13	48	16	14	478

Table A6. Frequency of errors in 30-minute man-machine rainfall in north and central during August.

	Man-Machine 30-minute amounts (inch)						
Error (inch)	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99	TOTAL
-0.50 to -0.99	1	0	0	0	0	0	1
-0.25 to -0.49	0	0	0	0	0	0	0
-0.11 to -0.24	3	0	0	2	1	0	6
-0.05 to -0.10	45	0	0	0	1	1	47
-0.01 to -0.04	135	0	0	18	1	0	154
0.05 to 0.10		0	0	6	4	1	11
0.11 to 0.24		0	0	0	1	1	2
0.25 to 0.49		0	0	0	0	0	0
0.50 to 0.99		0	0	0	0	2	2
TOTAL	184	0	0	26	8	5	223

Table A7. Frequency of percent error in 30-minute man-machine rainfall in north and central during June-July.

	Man-Machine 30-minute amounts (inch)						
Percent error	0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.99	TOTAL
-100	71	0	0	0	0	0	71
-70 to -99		0	0	1	0	0	1
-50 to -69		0	2	1	1	0	4
-20 to -49		0	0	0	0	2	2
-1 to -19		0	0	0	0	1	1
0	316	0	8	12	2	0	338
1 to 19		0	0	0	0	0	0
20 to 49		0	0	0	0	0	0
50 to 99		0	0	0	0	1	1
100 to 199		0	1	25	6	4	36
200 to 499		0	0	0	6	5	11
≥ 500		0	0	0	0	1	1
∞		0	2	9	1	0	12
TOTAL	387	0	13	48	16	14	478

Table A8. Frequency of percent error in 30-minute man-machine rainfall in north and central during August.

	Man-Machine 30-minute amounts (inch)						
Percent error	0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.99	TOTAL
-100	49	0	0	0	0	0	49
-70 to -99		0	0	0	0	0	0
-50 to -69		0	0	2	0	0	2
-20 to -49		0	0	0	2	0	2
-1 to -19		0	0	0	0	1	1
0	135	0	0	18	1	0	154
1 to 19		0	0	0	0	0	0
20 to 49		0	0	0	0	0	0
50 to 99		0	0	0	0	1	1
100 to 199		0	0	4	5	1	10
200 to 499		0	0	0	0	0	0
≥ 500		0	0	0	0	2	2
∞		0	0	2	0	0	2
TOTAL	184	0	0	26	8	5	223

Table A9. Frequency of errors in 30-minute radar-indicated rainfall measurements in north and central during June-July.

	Radar 30-minute amounts (inch)						
Error (inch)	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99	TOTAL
-0.50 to -0.99	0	0	0	1	0	0	1
-0.25 to -0.49	0	0	0	0	0	0	0
-0.11 to -0,24	3	0	0	1	1	0	5
-0.05 to -0.10	7	1	0	0	0	1	9
-0.01 to -0.04	18	5	2	2	0	1	28
0.0	219	10	0	0	0	0	229
0.01 to 0.04		121	15	0	0	0	136
0.05 to 0.10		0	14	13	1	0	28
0.11 to 0.24		0	0	5	10	2	17
0.25 to 0.49		0	0	0	0	7	7
TOTAL	247	137	31	22	12	11	460

Table A10. Frequency of errors in 30-minute radar-indicated rainfall measurements in north and central during August.

	Radar 30-minute amounts (inch)						
Error (inch)	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99	TOTAL
-0.50 to -0.99	1	0	0	0	0	0	1
-0.25 to -0.49	1	0	0	0	0	0	1
-0.11 to -0.24	2	0	0	0	0	0	2
-0.05 to -0.10	3	0	0	0	0	1	4
-0.01 to -0.04	5	2	3	0	0	0	10
0.0	72	7	0	0	0	0	79
0.01 to 0.04		71	12	7	3	0	93
0.05 to 0.10		0	10	8	4	6	28
0.11 to 0.24		0	0	1	6	2	9
0.25 to 0.49		0	0	0	0	1	1
TOTAL	84	80	25	16	13	10	228

Table A11. Frequency of percent error in 30-minute radar-indicated rainfall measurements in north and central during June-July.

	Radar 30-minute amounts (inch)						
Percent error	0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.99	TOTAL
-100	28	0	0	0	0	0	28
-70 to -99		1	0	1	0	0	2
-50 to -69		3	0	1	0	0	4
-20 to -49		2	1	0	1	0	4
-1 to -19		0	1	2	0	2	5
0	219	10	0	0	0	0	229
1 to 19		0	1	0	0	0	1
20 to 49		1	1	0	0	0	2
50 to 99		5	4	2	1	2	14
100 to 199		8	6	8	1	5	28
200 to 499		11	7	5	9	1	33
≥ 500		0	4	1	0	1	7
∞		96	6	2	0	0	103
TOTAL	247	137	31	22	12	11	460

Table A12. Frequency of percent error in 30-minute radar-indicated rainfall measurements in north and central during August.

Radar 30-minute amounts (inch)

Percent Error	0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 10.29	0.30- 0.99	TOTAL
-100	12	0	0	0	0	0	12
-70 to -99		0	0	0	0	0	0
-50 to -69		1	0	0	0	0	1
-20 to -49		1	2	0	0	0	3
-1 to -19		0	1	0	0	1	2
0	72	7	0	0	0	0	79
1 to 19		0	0	0	1	0	1
20 to 49		1	3	3	0	2	9
50 to 99		2	5	8	4	1	20
100 to 199		5	7	3	4	3	22
200 to 499		4	3	1	3	2	13
≥ 500		0	2	0	0	0	2
∞		59	2	1	1	1	64
TOTAL	84	80	25	16	13	10	228

Table A13. Frequency distribution of percent error and accumulative percent error of 30-minute rainfall.

	MSD Network				Man-Machine				Radar			
Error	June-July		August		June-July		August		June-July		August	
(inch)	%*	Cum %**	%	Cum %	%	Cum %	%	Cum %	%	Cum %	%	Cum %
-0.50 to -0.99	0.2	0.2	0.0	0.0	0.2	0.2	0.5	0.4	0.2	0.2	0.4	0.4
-0.25 to -0.49	0.0	0.2	0.4	0.4	0.0	0.2	0.0	0.4	0.0	0.2	0.4	0.8
-0.11 to -0.24	1.3	1.5	2.2	2.5	0.6	0.8	2.7	3.1	1.1	1.3	0.9	1.7
-0.05 to -0.10	2.5	4.0	3.9	6.5	15.7	16.5	21.1	24.2	2.0	3.3	1.8	3.5
-0.01 to -0.04	12.5	16.5	21.8	28.3	0.0	16.5	0.0	24.2	6.1	9.4	4.4	7.9
0.0	68.1	84.6	63.0	91.3	70.7	87.2	69.1	93.3	49.8	59.2	34.7	42.6
0.01 to 0.04	11.9	96.5	7.4	98.7	0.0	87.2	0.0	93.3	29.5	88.7	40.8	83.4
0.05 to 0.10	2.9	99.4	0.9	99.6	9.0	96.2	4.9	98.2	6.1	94.8	12.3	95.7
0.11 to 0.24	0.4	99.8	0.4	100.0	3.0	99.2	0.9	99.1	3.7	98.5	3.9	99.6
0.25 to 0.49	0.2	100.0	0.0	100.0	0.6	99.8	0.0	99.1	1.5	100.0	0.4	100.0
0.50 to 0.99	0.0	100.0	0.0	100.0	0.2	100.0	0.9	100.0	0.0	100.0	0.0	100.0
N	480		230		478		223		460		228	

* Percent (%)
** Cumulative Percent (Cum %)

Table A14. Percent of 30-minute monitored rainfall amounts with an error of 0.05 inch or less.

30-Minute Monitored Amounts (Inch)	MSD				Man-Machine				Radar			
	June-July		August		June-July		August		June-July		August	
	N	%	N	%	N	%	N	%	N	%	N	%
0.0	336	97.6	150	98.7	387	81.7	184	73.4	247	96.0	84	91.7
0.01-0.04	92	97.8	34	91.2	0	0.0	0	0.0	137	99.3	80	100.0
0.05-0.09	30	70.0	23	87.0	13	61.5	0	0.0	31	54.8	25	60.0
0.10-0.19	14	21.4	17	70.6	48	25.0	26	69.2	22	9.1	16	43.8
0.20-0.29	5	20.0	3	33.3	16	12.5	8	12.5	12	0.0	13	7.7
0.30-0.99	3	33.3	3	0.0	14	0.0	5	0.0	11	9.1	10	0.0

Table A15. Percent of 30-minute rain amounts with a percent error of less than 50%.

30-Minute Monitored Amounts (Inch)	MSD				Man-Machine				Radar			
	June-July		August		June-July		August		June-July		August	
	N	%	N	%	N	%	N	%	N	%	N	%
0.0	336	89.0	150	87.3	387	81.7	184	73.4	247	88.7	84	85.7
0.01-0.04	92	32.6	34	35.3	0	0.0	0	0.0	137	9.5	80	11.3
0.05-0.09	30	46.7	23	82.6	13	61.5	0	0.0	31	12.9	25	24.0
0.10-0.19	14	28.6	17	94.1	48	25.0	26	69.2	22	9.1	16	18.8
0.20-0.29	5	60.0	3	100.0	16	12.5	8	37.5	12	8.3	13	7.7
0.30-0.99	3	100.0	3	66.7	14	21.4	5	20.0	9	22.2	3	10.0

Table A16. Frequency of error in accumulated rainfall measurements by MSD network in north and central during June-July.

	MSD accumulated amounts (inch)										
Error (Inch)	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
-0.50 to -0.99	0	0	0	0	0	0	2	0	0	0	2
-0.25 to -0.49	1	0	0	0	0	1	2	0	0	0	4
-0.11 to -0.24	2	0	2	0	4	9	5	0	0	0	22
-0.05 to -0.01	3	2	1	3	22	11	0	0	0	0	42
-0.01 to -0.04	41	29	9	16	8	5	3	0	0	0	111
0	174	7	2	3	0	0	0	0	1	0	187
0.01 to 0.04	0	41	3	20	9	0	0	0	4	0	77
0.05 to 0.10	0	0	1	2	3	2	0	0	0	0	8
0.11 to 0.24	0	0	0	0	2	17	5	0	0	0	24
0.25 to 0.49	0	0	0	0	3	0	0	0	0	0	3
TOTAL	221	79	18	44	51	45	17	0	5	0	480

Table A17. Frequency of error in accumulated rainfall measurements by MSD network in north and central during August.

	MSD accumulated amounts (inch)										
Error (Inch)	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥ 1.5	Total
-0.50 to -0.99	0	0	0	0	0	0	1	4	0	0	5
-0.25 to -0.49	0	9	0	0	0	4	6	0	0	0	19
-0.11 to -0.24	0	1	0	1	0	1	17	0	0	0	20
-0.05 to -0.10	6	1	7	1	3	10	4	0	0	0	32
-0.01 to -0.04	9	11	4	13	7	1	0	0	0	0	45
0	63	2	0	0	0	0	0	0	0	0	65
0.01 to 0.04	0	4	0	1	2	1	0	0	0	0	8
0.05 to 0.10	0	0	6	0	0	1	10	0	0	0	17
0.11 to 0.24	0	0	0	0	0	0	5	3	11	0	19
TOTAL	78	28	17	16	12	18	43	7	11	0	230

Table A18. Frequency of percent error in accumulated rainfall measurements by MSD network in north and central during June-July.

	Radar accumulated amount (inch)										
Percent Error	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
-100	47	0	0	0	0	0	0	0	0	0	47
-70 to -99		4	1	0	0	0	0	0	0	0	5
-50 to -69		20	2	0	0	0	0	0	0	0	22
-20 to -49		7	8	6	22	13	5	0	0	0	61
-1 to -19		0	1	13	12	13	7	0	0	0	46
0	174	7	2	3	0	0	0	0	1	0	187
1 to 19		0	0	11	9	0	0	0	4	0	24
20 to 49		1	2	6	2	5	0	0	0	0	16
50 to 99		9	0	4	0	10	5	0	0	0	28
100 to 199		5	0	1	3	4	0	0	0	0	13
200 to 499		1	1	0	0	0	0	0	0	0	2
≥500		0	1	0	0	0	0	0	0	0	1
∞		25	0	0	3	0	0	0	0	0	28
TOTAL	221	79	18	44	51	45	17	0	5	0	480

Table A19. Frequency of percent error in accumulated rainfall measurements by MSD network in north and central during August.

	Radar accumulated amounts (inch)										
Percent Error	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
-100	15	0	0	0	0	0	0	0	0	0	15
-70 to -99		12	0	0	0	0	0	0	0	0	12
-50 to -69		10	7	0	0	1	0	0	0	0	18
-20 to -49		0	2	8	2	8	8	4	0	0	32
-1 to -19		0	2	7	8	7	20	0	0	0	44
0	63	2	0	0	0	0	0	0	0	0	65
1 to 19		0	0	0	2	2	7	0	9	0	20
20 to 49		0	0	0	0	0	7	3	2	0	12
50 to 99		0	0	1	0	0	1	0	0	0	2
100 to 199		0	1	0	0	0	0	0	0	0	1
200 to 499		0	4	0	0	0	0	0	0	0	4
≥500		0	0	0	0	0	0	0	0	0	0
∞		4	1	0	0	0	0	0	0	0	5
TOTAL	78	28	17	16	12	18	43	7	11	0	230

Table A20. Frequency of error in accumulated rainfall estimates by man-machine in north and central during June-July.

Error (Inch)	Man-Machine accumulated amounts (inch) 0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥ 1.5	Total
-0.25 to -0.49	4	0	2	4	1	2	0	0	1	0	14
-0.11 to -0.24	3	0	0	0	0	2	1	0	1	0	7
-0.05 to -0.10	51	0	0	0	0	1	2	0	3	0	57
-0.01 to -0.04	0	0	0	0	0	0	0	0	0	0	0
0	180	0	2	21	5	1	0	2	0	0	211
0.01 to 0.04	0	0	0	0	0	0	0	0	0	0	0
0.05 to 0.10	0	0	0	61	8	7	0	0	0	0	76
0.11 to 0.24	0	0	0	0	18	3	11	0	3	0	35
0.25 to 0.49	0	0	0	0	0	2	14	0	2	0	18
0.50 to 0.99	0	0	0	0	0	3	11	7	25	0	46
≥1.0	0	0	0	0	0	0	0	0	14	0	14
TOTAL	238	0	4	86	32	21	39	9	49	0	478

Table A21. Frequency of error in accumulated rainfall estimates by man-machine in north and central during August.

Man-Machine accumulated amounts (inch)

Error (Inch)	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
-0.50 to -0.99	1	0	0	0	0	0	0	1	3	0	5
-0.25 to -0.49	9	0	0	0	0	0	11	2	0	0	22
-0.11 to -0.24	2	0	0	0	0	0	5	0	0	0	7
-0.05 to -0.10	26	0	0	0	6	0	0	0	0	0	32
-0.01 to -0.04	0	0	0	0	0	0	0	0	0	0	0
0	66	0	0	12	2	8	12	6	0	0	106
0.01 to 0.04	0	0	0	0	0	0	0	0	0	0	0
0.05 to 0.10	0	0	0	2	11	1	9	1	0	0	24
0.11 to 0.24	0	0	0	0	0	3	4	0	11	0	18
0.25 to 0.49	0	0	0	0	0	1	5	0	3	0	9
TOTAL	104	0	0	14	19	13	46	10	17	0	223

Table A22. Frequency of percent error in accumulated rainfall estimates by man-machine in north and central during June-July.

	Man-Machine accumulated amounts (inch)										
Percent Error	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
-100	58	0	0	0	0	0	0	0	0	0	58
-70 to -99		0	2	4	0	0	0	0	0	0	6
-50 to -69		0	0	0	1	0	0	0	0	0	1
-20 to -49		0	0	0	0	5	1	0	2	0	8
-1 to -19		0	0	0	0	0	2	0	3	0	5
0	180	0	2	21	5	1	0	2	0	0	211
1 to 19		0	0	0	0	0	0	0	3	0	3
20 to 49		0	0	0	0	2	3	0	1	0	6
50 to 99		0	0	1	0	5	8	0	1	0	15
100 to 199		0	0	30	17	0	10	5	14	0	76
200 to 499		0	0	10	8	7	13	1	24	0	63
≥500		0	0	0	0	0	0	0	1	0	1
∞		0	0	20	1	1	2	1	0	0	25
TOTAL	238	0	4	86	32	21	39	9	49	0	478

Table A23. Frequency of percent error in accumulated rainfall estimates by man-machine in north and central during August.

	Man-Machine accumulated amounts (inch)										
Percent Error	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
-100	38	0	0	0	0	0	0	0	0	0	38
-70 to -99		0	0	0	0	0	0	0	0	0	0
-50 to -69		0	0	0	0	0	0	0	0	0	0
-20 to -49		0	0	0	6	0	16	3	3	0	28
-1 to -19		0	0	0	0	0	0	0	0	0	0
0	66	0	0	12	2	8	12	6	0	0	106
1 to 19		0	0	0	0	0	5	1	0	0	6
20 to 49		0	0	0	0	1	5	0	13	0	19
50 to 99		0	0	0	0	1	6	0	1	0	8
100 to 199		0	0	2	11	1	0	0	0	0	14
200 to 499		0	0	0	0	2	2	0	0	0	4
TOTAL	104	0	0	14	19	13	46	10	17	0	223

Table A24. Frequency of errors in accumulated rainfall estimates by man-machine in north and central during June-July.

Error (Inch)	Man-Machine accumulated amounts (inch)										
	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
≥-1.0	1	0	0	0	0	0	0	0	0	0	1
-0.50 to -0.99	0	0	0	0	0	0	0	0	0	0	0
-0.25 to -0.49	4	2	0	8	2	0	0	0	1	0	17
-0.11 to -0.24	4	0	0	0	1	1	1	0	4	0	11
-0.05 to -0.10	2	3	0	0	0	0	1	1	0	0	7
-0.01 to -0.04	3	2	1	0	0	0	0	2	0	0	8
0	45	5	0	0	0	0	0	0	0	0	50
0.01 to 0.04	0	133	13	2	1	0	0	0	0	0	149
0.05 to 0.10	0	0	47	10	1	0	0	0	0	0	58
0.11 to 0.24	0	0	0	25	31	22	2	0	0	0	80
0.25 to 0.49	0	0	0	0	0	5	13	3	1	0	22
0.50 to 0.99	0	0	0	0	0	0	7	9	25	4	45
≥ 1.0	0	0	0	0	0	0	0	0	12	0	12
TOTAL	59	145	61	45	36	28	24	15	43	4	460

Table A25. Frequency of error in accumulated radar-indicated rainfall measurements in north and central during August.

	Radar accumulated amounts (inch)										
Error (Inch)	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
-0.50 to -0.99	3	6	0	0	0	0	0	0	0	0	9
-0.25 to -0.49	3	6	0	0	0	0	0	0	0	0	9
-0.11 to -0.24	2	0	0	0	0	0	0	0	0	0	2
-0.05 to -0.10	1	0	0	0	1	0	0	0	0	0	2
-0.01 to -0.04	8	0	1	0	0	0	0	0	0	0	9
0	19	0	0	0	0	0	0	0	0	0	19
0.01 to 0.04	0	27	0	1	0	0	0	0	0	0	28
0.05 to 0.10	0	0	15	5	2	0	0	1	0	0	23
0.11 to 0.24	0	0	0	13	16	6	3	1	2	0	41
0.25 to 0.49	0	0	0	0	2	4	11	9	11	0	37
0.50 to 0.99	0	0	0	0	0	0	1	10	17	18	46
≥1.0	0	0	0	0	0	0	0	0	0	3	3
TOTAL	36	39	16	19	21	10	15	21	30	21	228

Table A26. Frequency of percent error in accumulated radar-indicated rainfall measurements in north and central during June-July.

	Radar accumulated amounts (inch)										
Percent Error	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
-100	14	.0	0	0	0	0	0	0	0	0	14
-70 to -99		3	0	4	0	0	0	0	0	0	7
-50 to -69		4	0	4	2	0	0	0	0	0	10
-20 to -49		0	1	0	1	1	0	0	0	0	3
-1 to -19		0	0	0	0	0	2	3	5	0	10
0	45	5	0	0	0	0	0	0	0	0	50
1 to 19		0	0	1	1	0	0	0	0	0	2
20 to 49		0	2	1	0	0	0	0	0	0	3
50 to 99		0	2	1	0	10	2	3	1	4	23
100 to 199		2	2	6	17	12	4	2	9	0	54
200 to 499		10	21	7	6	5	15	7	28	0	99
≥500		0	6	14	9	0	1	0	0	0	30
∞		121	27	7	0	0	0	0	0	0	155
TOTAL	59	145	61	45	36	28	24	15	43	4	460

Table A27. Frequency of percent error in accumulated radar-indicated rainfall measurements in north and central during August.

	Radar accumulated amounts (inch)										
Percent Error	0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.49	0.50-0.74	0.75-0.99	1.00-1.49	≥1.5	Total
-100	17	0	0	0	0	0	0	0	0	0	17
-70 to -99		12	0	0	0	0	0	0	0	0	12
-50 to -69		0	0	0	0	0	0	0	0	0	0
-20 to -49		0	1	0	0	0	0	0	0	0	1
-1 to -19		0	0	0	1	0	0	0	0	0	1
0	19	0	0	0	0	0	0	0	0	0	19
1 to 19		0	0	1	0	0	0	1	2	0	4
20 to 49		0	0	1	0	0	1	1	0	0	3
50 to 99		0	0	2	2	3	11	9	25	18	70
100 to 199		0	0	1	5	3	0	0	1	0	10
200 to 499		0	1	0	3	3	2	6	1	3	19
≥500		0	0	6	10	1	1	4	1	0	23
∞		27	14	8	0	0	0	0	0	0	49
TOTAL	36	39	16	19	21	10	15	21	30	21	228

Table A28. Frequency distribution of percent error and cumulative percent error of monitored accumulated rainfall.

Accumulated error (inch)	MSD				Man-Machine				Radar			
	June-July		August		June-July		August		June-July		August	
	%*	Cum %**	%	Cum %	%	Cum %	%	Cum %	%	Cum %	%	Cum %
<-1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0
-0.50 to -0.99	0.4	0.4	2.2	2.2	0.0	0.0	2.2	2.2	0.0	0.2	3.9	3.9
-0.25 to -0.49	0.8	1.2	8.2	10.4	2.9	2.9	9.9	12.1	3.7	3.9	3.9	7.8
-0.11 to -0.24	4.6	5.8	8.7	19.1	1.5	4.4	3.1	15.2	2.4	6.3	0.9	8.7
-0.05 to -0.10	8.8	14.6	13.9	33.0	11.9	16.3	14.4	29.6	1.5	7.8	0.9	9.6
-0.01 to -0.04	23.1	37.7	19.6	52.6	0.0	16.3	0,0	29.6	1.7	9.5	3.9	13.5
0.0	39.0	76.7	28.3	80.9	44.2	60.5	47.5	77.1	10.9	20.4	8.4	21.9
0.01 to 0.04	16.0	92.7	3.5	84.4	0.0	60.5	0.0	77.1	32.4	52.8	12.3	34.2
0.05 to 0.10	1.7	94.4	7.4	91.8	15.9	76.4	10.8	87.9	12.6	65.4	10.1	44.3
0.11 to 0.24	5.0	99.4	8.2	100.0	7.3	83.7	8.1	96.0	17.4	82.8	18.0	62.3
0.25 to 0.49	0.6	100.0	0.0	100.0	3.8	87.5	4.0	100.0	4.8	87.6	16.2	78.5
0.50 to 0.99	0.0	100.0	0.0	100.0	9.6	97.1	0.0	100.0	9.8	97.4	20.2	98.7
≥1.0	0.0	100.0	0.0	100.0	2.9	100.0	0.0	100.0	2.6	100.0	1.3	100.0
N	480		230		478		223		460		228	

* Percent (%)
** Cumulative Percent (Cum %)

Table A29. Percent of accumulated rainfall amounts with an error of 0.1 inch or less.

Monitored Accumulated Amounts (Inch)	MSD				Man-Machine				Radar			
	June-July		August		June-July		August		June-July		August	
	N	%	N	%	N	%	N	%	N	%	N	%
0.0	221	98.6	78	100.0	238	97.1	104	88.5	59	84.7	36	77.8
0.01-0.04	79	100.0	28	64.3	0	0.0	0	0.0	145	98.6	39	69.2
0.05-0.09	18	88.9	17	100.0	4	50.0	0	0.0	61	100.0	16	100.0
0.10-0.19	44	100.0	16	93.8	86	95.4	14	100.0	45	26.7	19	31.6
0.20-0.29	51	82.4	12	100.0	32	40.6	19	100.0	36	5.6	21	14.3
0.30-0.49	45	40.0	18	72.2	21	42.9	13	69.2	28	0.0	10	0.0
0.50-0.74	17	17.6	43	32.6	39	5.1	46	45.7	24	4.2	15	0.0
0.75-0.99	0	0.0	7	0.0	9	22.2	10	70.0	15	20.0	21	4.7
1.00-1.49	5	100.0	11	0.0	49	6.1	17	0.0	43	0.0	30	0.0
≥1.5	0	0.0	0	0.0	0	0.0	0	0.0	4	0.0	21	0.0

Table A30. Percent of accumulated rain amounts with a percent error of less than 50%.

Accumulated Amounts (Inch)	MSD				Man-Machine				Radar			
	June-July		August		June-July		August		June-July		August	
	N	%	N	%	N	%	N	%	N	%	N	%
0.0	221	78.7	78	80.8	238	75.6	104	63.5	59	76.3	36	52.8
0.01-0.04	79	19.0	28	7.1	0	0.0	0	0.0	121	4.1	27	3.7
0.05-0.09	18	72.2	17	23.5	4	50.0	0	0.0	61	4.9	16	0.0
0.10-0.19	44	88.6	16	93.8	86	24.4	14	85.7	45	4.4	19	10.5
0.20-0.29	51	90.2	12	100.0	32	15.6	19	42.1	36	5.6	21	4.8
0.30-0.49	45	68.9	18	94.4	21	38.1	13	69.2	28	3.6	10	0.0
0.50-0.74	17	70.6	43	97.7	39	15.4	46	82.6	24	8.3	15	6.7
0.75-0.99	0	0.0	7	100.0	9	22.2	10	100.0	15	20.0	21	9.5
1.00-1.49	5	100.0	11	100.0	49	18.4	17	94.1	43	11.6	30	6.7
≥1.5	0	0.0	0	0.0	0	0.0	0	0.0	4	0.0	21	0.0

APPENDIX B

DETAILED ANALYSES OF RAINSTORM FORECASTING DURING 1979

Tables B1 to B26 provide detailed information on the distribution of errors in the forecasting of 30-, 60-, and 120-minute expected additional rainfall. The standard of comparison is the dense raingage network (Fig. 4) operated by the Water Survey in the Chicago urban area during the 1979 demonstration period, 18 June to 15 August. This network has a gage spacing of approximately 3 miles, a distance previous research had shown to provide accurate measurements of areal mean rainfall.

Forecast errors were determined for 1) the man-machine combination, in which the duty meteorologist would adjust, if necessary, the objective forecasts on the basis of available meteorological information not available to the objective technique (Tables B1 to B4), and 2) the objective forecast technique, based on the unadjusted radar-indicated rainfall measurements (Tables B5 to B8). Tables B9 to B13 present comparisons between forecast methods. Analyses were performed separately for June-July and August, because limited telemetered raingage data became available in August for use by the duty meteorologist. Furthermore, forecasting errors have been classified as either underestimates or overestimates. Errors have been defined in inches of rainfall and percentages.

Tables B14 to B26 are analogous to the tables for rain forecasts of 30-, 60-, and 120-minutes, but are based on forecasts of accumulated rainfall amounts expected in the next 30-, 60-, and 120-minutes for each storm in the demonstration period.

No text is included with this Appendix since the tables are considered self-explanatory, and interpretation is left to the judgement of the reader.

Table B1. Frequency distribution of errors in man-machine forecasts of 30-, 60-, and 120-minute rainfall for north and central sections during June-July.

				30-Minute Forecast Error (inch)							60-Minute Forecast Error (inch)								120-Minute Forecast Error (inch)				
Forecast Categories (inch)	N	N_p^*		0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	N	N_p		0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	N	N_p		0.01-0.04	0.05-0.10	0.11-0.24	0.24-0.49	0.50-0.99
0.0	436	379	-	54	2	1	0	389	321	-	55	12	1	0	0	296	212	-	58	16	10	0	0
0.01-0.04	6	2	+	4	0	0	0	6	0	+	4	0	0	0	0	9	3	+	5	0	0	0	0
			-	0	0	0	0			-	2	0	0	0	0			-	1	0	0	0	0
0.05-0.09	9	0	+	5	4	0	0	7	1	+	4	2	0	0	0	8	2	+	1	4	0	0	0
			-	0	0	0	0			-	0	0	0	0	0			-	0	0	0	1	0
0.10-0.19	36	0	+	7	26	0	0	38	0	+	6	25	2	0	0	50	1	+	10	21	3	0	0
			-	1	1	1	0			-	2	1	2	0	0			-	8	2	3	1	1
0.20-0.29	19	0	+	1	3	10	0	15	0	+	2	5	7	0	0	13	1	+	0	2	9	0	0
			-	2	0	3	0			-	1	0	0	0	0			-	0	0	1	0	0
0.30-0.99	9	0	+	0	0	3	5	28	0	+	0	2	8	10	2	41	1	+	2	4	10	13	3
			-	0	0	1	0			-	0	0	3	2	1			-	1	0	2	2	3
≥1.00	0	0	+	0	0	0	0	1	0	+	0	0	1	0	0	5	0	+	0	0	1	0	3
			-	0	0	0	0			-	0	0	0	0	0			-	0	0	1	0	0
TOTAL	515	381	+	17	33	13	5	484	322	+	16	34	18	10	2	422	220	+	18	31	23	13	6
			-	57	3	6	0			-	60	13	6	2	1			-	68	18	17	4	4

*Number of perfect forecasts

Table B2. Frequency distribution of errors in man-machine forecasts of 30-, 60-, and 120-minute rainfall for north and central sections during August.

Forecast Categories (inch)	N	N_p		30-Minute Forecast Error (inch)				N	N_p		60-Minute Forecast Error (inch)					N	N_p		120-Minute Forecast Error (inch)				
				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99
0.00	157	118	-	36	3	0	0	125	84	-	28	9	3	1	0	84	40	-	22	9	8	3	2
0.01-0.04	0	0	+	0	0	0	0	0	0	+	0	0	0	0	0	2	0	+	0	0	0	0	0
			-	0	0	0	0			-	0	0	0	0	0			-	0	0	1	1	0
0.05-0.09	1	0	+	0	0	0	0	1	0	+	0	0	0	0	0	1	0	+	0	0	0	0	0
			-	1	0	0	0			-	1	0	0	0	0			-	1	0	0	0	0
0.10-0.19	29	2	+	10	10	0	0	28	0	+	2	16	0	0	0	34	1	+	2	16	2	0	0
			-	5	0	2	0			-	5	3	1	0	1			-	6	4	1	1	1
0.20-0.29	9	0	+	2	1	4	0	17	1	+	3	7	3	0	0	12	0	+	2	1	3	0	0
			-	0	0	1	1			-	1	1	0	1	0			-	0	3	2	1	0
0.30-0.99	2	0	+	0	1	0	1	11	0	+	1	1	6	1	0	22	2	+	3	4	4	2	1
			-	0	0	0	0			-	0	1	0	1	0			-	2	3	0	1	0
TOTAL	198	120	+	12	12	4	1	182	85	+	6	24	9	1	0	155	43	+	7	21	9	2	1
			-	42	3	3	1			-	35	14	4	3	1			-	31	19	12	7	3

Table B3. Frequency distribution of percent error in man-machine forecasts of 30-, 60-, and 120-minute rainfall for north and central sections during June-July.

Percent Error	30-Minute Forecast Range (Inch)							60-Minute Forecast Range (Inch)								120-Minute Forecast Range (Inch)							
	0.0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99	N	0.0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99	≥1.0	N	0.0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99	≥1.0	N
∞		3	4	5	0	0	12		2	2	6	1	0	0	11		2	4	7	1	1	0	15
≥ 500		0	0	4	5	3	12		0	0	5	4	6	0	15		0	0	5	6	5	0	16
100 to 499		0	4	17	5	4	30		2	3	16	2	10	0	33		3	1	12	3	12	3	34
50 to 99		1	0	1	1	1	4		0	0	3	5	4	0	12		0	0	4	1	5	0	10
20 to 49		0	1	4	3	0	8		0	1	3	1	0	0	5		0	0	5	0	6	0	11
1 to 19		0	0	2	0	0	2		0	0	0	1	2	1	4		0	0	1	0	3	1	5
0	379	2	0	0	0	0	381	321	0	1	0	0	0	0	322	212	3	2	1	1	1	0	220
-1 to -19		0	0	1	2	1	4		0	0	1	1	0	0	2		0	0	5	0	1	1	7
-20 to -49		0	0	1	0	0	1		2	0	2	0	4	0	8		1	0	4	1	4	0	10
-50 to -69		0	0	1	3	0	4		0	0	2	0	2	0	4		0	0	4	0	3	0	7
-70 to -99		0	0	0	0	0	0		0	0	0	0	0	0	0		0	1	2	0	0	0	3
-100	57						57	68							68	84							84
TOTAL	436	6	9	36	19	9	515	389	6	7	38	15	28	1	484	296	9	8	50	13	41	5	422

Table B4. Frequency distribution of percent error in man-machine forecast of 30-, 60-, and 120-minute rainfall for north and central sections during August.

	30-Minute Forecast Range (Inch)							60-Minute Forecast Range (Inch)								120-Minute Forecast Range (Inch)							
Percent Error	0.0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99	N	0.0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99	≥1.0	N	0.0	0.01-0.04	0.05-0.09	0.10-0.19	0.20-0.29	0.30-0.99	≥1.0	N
∞		0	0	3	1	0	4		0	0	5	1	0	0	6		0	0	6	0	0	0	6
-500		0	0	2	0	0	2		0	0	5	0	0	0	5		0	0	6	1	0	0	7
100 to 499		0	0	5	2	1	8		0	0	6	2	3	0	11		0	0	6	2	3	0	11
50 to 99		0	0	3	2	1	6		0	0	1	5	3	0	9		0	0	0	1	2	0	3
20 to 49		0	0	6	0	0	6		0	0	1	3	2	0	6		0	0	2	0	4	0	6
1 to 19		0	0	1	2	0	3		0	0	0	2	1	0	3		0	0	0	2	5	0	7
0	118	0	0	2	0	0	120	84	0	0	0	1	0	0	85	40	0	0	1	0	2	0	43
-1 to -19		0	1	3	0	0	4		0	1	3	1	1	0	6		0	1	3	0	4	0	8
-20 to -49		0	0	2	0	0	2		0	0	5	1	1	0	7		0	0	5	5	2	0	12
-50 to -69		0	0	2	2	0	4		0	0	1	1	0	0	2		0	0	2	1	0	0	3
-70 to -99		0	0	0	0	0	0		0	0	1	0	0	0	1		2	0	3	0	0	0	5
-100	39						39	41							41	44							44
TOTAL	157	0	1	29	9	2	198	125	0	1	28	17	11	0	182	84	2	1	34	12	22	0	155

Table B5. Frequency of errors between objective forecasts of 30-, 60-, and 120-minute rainfall for north and central during June-July.

				30-Minute Forecast							60-Minute Forecast								120-Minute Forecast					
				Error (Inch)							Error (Inch)								Error (Inch)					
Forecast categories (inch)	N	N_p		0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	N	N_p		0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	N	N_p		0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0
0.0	418	371	-	40	6	1	0	360	306	-	39	12	3	0	0	277	197	-	42	20	12	4	1	1
0.01-0.04	57	14	+	26	0	0	0	57	7	+	26	0	0	0	0	51	6	+	25	0	0	0	0	0
			-	16	1	0	0			-	17	3	4	0	0			-	13	5	2	0	0	0
0.05-0.09	15	1	+	9	4	0	0	22	0	+	9	10	0	0	0	28	1	+	10	5	0	0	0	0
			-	0	0	0	1			-	2	1	0	0	0			-	3	3	4	2	0	0
0.10-0.19	13	0	+	2	9	1	0	19	0	+	3	3	7	0	0	19	0	+	3	6	4	0	0	0
			-	0	0	1	0			-	2	2	1	0	1			-	1	2	1	0	2	0
0.20-0.29	9	0	+	0	1	6	0	5	0	+	0	1	2	0	0	15	1	+	1	3	5	2	0	0
			-	0	0	2	0			-	0	0	1	1	0			-	0	2	1	0	0	0
0.30-0.99	8	0	+	0	0	3	4	21	0	+	0	1	7	9	2	28	0	+	1	1	6	14	5	0
			-	1	0	0	0			-	0	0	1	0	1			-	0	0	0	0	1	0
≥1.0	0	0	+	0	0	0	0	2	0	+	0	0	0	0	2	6	0	+	0	0	0	0	5	0
			-	0	0	0	0			-	0	0	0	0	0			-	0	0	1	0	0	0
TOTAL	520	386	+	37	14	10	4	486	313	+	38	15	16	9	4	424	205	+	40	15	15	16	10	0
			-	57	7	4	1			-	60	18	10	1	2			-	59	32	21	6	4	1

Table B6. Frequency distribution of errors in objective forecasts of 30-, 60-, and 120-tninute rainfall for north and central during August.

Forecast categories (inch)	N	Np		30-Minute Forecast Error (Inch)			
				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49
0.0	138	118	-	20	0	0	0
0.01-0.04	27	2	+	14	0	0	0
			-	10	1	0	0
0.05-0.09	14	3	+	5	4	0	0
			-	2	0	0	0
0.10-0.19	15	0	+	6	7	2	0
			-	0	0	0	0
0.20-0.29	9	0	+	0	4	3	0
			-	0	1	1	0
0.30-0.99	5	0	+	0	1	1	2
			-	1	0	0	0
≥1.0			+				
			-				
TOTAL	208	123	+	25	16	6	2
			-	33	2	1	0

Forecast categories (inch)	N	Np		60-Minute Forecast Error (Inch)				
				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99
0.0	105	81	-	20	1	2	1	0
0.01-0.04	31	2	+	14	0	0	0	0
			-	11	3	1	0	0
0.05-0.09	10	1	+	4	1	0	0	0
			-	2	2	0	0	0
0.10-0.19	15	0	+	2	4	4	0	0
			-	4	0	0	1	0
0.20-0.29	13	1	+	0	3	8	0	0
			-	0	1	0	0	0
0.30-0.99	16	0	+	0	0	6	7	1
			-	0	2	0	0	0
≥1.0			+					
			-					
TOTAL	190	85	+	20	8	18	7	1
			-	37	9	3	2	0

Forecast categories (inch)	N	Np		120-Minute Forecast Error (Inch)					
				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0
0.0	70	35	-	20	3	8	2	2	0
0.01-0.04	20	1	+	10	0	0	0	0	0
			-	5	2	2	0	0	0
0.05-0.09	15	1	+	6	2	0	0	0	0
			-	1	4	0	0	1	0
0.10-0.19	16	0	+	2	3	5	0	0	0
			-	0	4	1	0	1	0
0.20-0.29	13	0	+	1	4	3	1	0	0
			-	1	2	1	0	0	0
0.30-0.99	21	0	+	2	2	4	5	4	0
			-	1	1	1	1	0	0
≥1.0	3	0	+	0	0	0	0	2	1
			-	0	0	0	0	0	0
TOTAL	158	37	+	21	11	12	6	6	1
			-	28	16	13	3	4	0

Table B7. Frequency distribution of percent error in objective forecasts of 30-, 60-, and 120-minute rainfall for north and central during June-July.

30-Minute Forecast

Percent Error	Range (Inch)							
	0.0	0.01-0.04	0.05-0.09	0.1-0.19	0.2-0.29	0.3-0.99	≥1.0	N
∞		14	1	0	0	0		15
≥500		0	0	0	2	2		4
100 to 499		10	8	8	2	3		31
50 to 99		2	3	1	2	2		10
20 to 49		0	1	3	1	0		5
1 to 19		0	0	0	0	0		0
0	371	14	1	0	0	0		386
-1 to -19		0	0	0	0	1		1
-20 to -49		4	0	0	2	0		6
-50 to -69		11	0	1	0	0		12
-70 to -99		2	1	0	0	0		3
-100	47	0	0	0	0	0		47
TOTAL	418	57	15	13	9	8		520

60-Minute Forecast

Percent Error	Range (Inch)							
	0.0	0.01-0.04	0.05-0.09	0.1-0.19	0.2-0.29	0.3-0.99	≥1.0	N
∞		15	3	1	0	0	0	19
≥500		0	3	4	1	5	0	13
100 to 499		8	8	3	1	10	2	32
50 to 99		3	2	2	1	2	0	10
20 to 49		0	3	2	0	0	0	5
1 to 19		0	0	1	0	2	0	3
0	306	7	0	0	0	0	0	313
-1 to -19		0	1	1	0	1	0	3
-20 to -49		5	1	3	1	1	0	11
-50 to -69		10	1	1	1	0	0	13
-70 to -99		9	0	1	0	0	0	10
-100	54	0	0	0	0	0	0	54
TOTAL	360	57	22	19	5	21	2	486

120-Minute Forecast

Percent Error	Range (Inch)							
	0.0	0.01-0.04	0.05-0.09	0.1-0.19	0.2-0.29	0.3-0.99	≥1.0	N
∞		15	1	1	3	0	0	20
≥500		0	3	3	3	6	0	15
100 to 499		10	8	4	1	12	5	40
50 to 99		0	0	2	3	3	0	8
20 to 49		0	2	2	0	3	0	7
1 to 19		0	1	1	1	3	0	6
0	197	6	1	0	1	0	0	205
-1 to -19		0	2	1	0	0	1	4
-20 to -49		3	3	2	3	0	0	11
-50 to -69		11	5	1	0	1	0	18
-70 to -99		6	2	2	0	0	0	10
-100	80	0	0	0	0	0	0	80
TOTAL	277	51	28	19	15	28	6	424

Table B8. Frequency distribution of percent error in objective forecasts of 30-, 60-, and 120-minute forecasts for north and central during August.

	30-Minute Forecast								60-Minute Forecast								120-Minute Forecast							
	Range (Inch)								Range (Inch)								Range (Inch)							
Percent Error	0.0	0.01-0.04	0.05-0.09	0.1-0.19	0.2-0.29	0.3-0.99	≥1.0	N	0.0	0.01-0.04	0.05-0.09	0.1-0.19	0.2-0.29	0.3-0.99	≥1.0	N	0.0	0.01-0.04	0.05-0.09	0.1-0.19	0.2-0.29	0.3-0.99	≥1.0	N
∞		10	2	0	0	1	0	13		12	1	2	1	0	0	16		9	2	1	1	0	0	13
≥500		0	2	0	0	0	0	2		0	0	2	1	0	0	3		0	0	5	2	1	0	8
100 to 499		2	1	7	2	2	0	14		2	1	4	3	9	0	19		1	1	1	1	7	3	14
50 to 99		1	2	3	2	0	0	8		0	1	0	4	2	0	7		0	3	1	2	3	0	9
20 to 49		1	2	2	3	0	0	8		0	2	0	2	3	0	7		0	2	1	2	4	0	9
1 to 19		0	0	3	0	1	0	4		0	0	2	0	0	0	2		0	0	1	1	2	0	4
0	118	2	3	0	0	0	0	123	81	2	1	0	1	0	0	85	35	1	1	0	0	0	0	37
-1 to -19		0	0	0	0	1	0	1		0	1	3	0	2	0	6		0	1	0	2	3	0	6
-20 to -49		3	2	0	2	0	0	7		5	2	1	1	0	0	9		2	3	4	2	1	0	12
-50 to -69		5	0	0	0	0	0	5		7	1	0	0	0	0	8		2	1	1	0	0	0	4
-70 to -99		3	0	0	0	0	0	3		3	0	1	0	0	0	4		5	1	1	0	0	0	7
-100	20							20	24							24	35							35
TOTAL	138	27	14	15	9	5	0	208	105	31	10	15	13	16	0	190	70	20	15	16	13	21	3	158

Table B9. Percent and cumulative percent error of 30-minute forecasts for north and central sections.

Error (inch)	Man-Machine June-July		Man-Machine August		Objective June-July		Objective August	
	%*	Cum %**	%	Cum %	%	Cum %	%	Cum %
-0.49 to -0.25	0.0	0.0	0.5	0.5	0.2	0.2	0.0	0.0
-0.24 to -0.11	1.2	1.2	1.5	2.0	0.8	1.0	0.5	0.5
-0.10 to -0.05	0.6	1.8	1.5	3.5	1.3	2.3	1.0	1.5
-0.04 to -0.01	11.1	12.9	21.2	24.7	11.0	13.3	15.8	17.3
0.0	73.9	86.8	60.6	85.3	74.2	87.5	59.1	76.4
0.01 to 0.04	3.3	90.1	6.1	91.4	7.1	94.6	12.0	88.4
0.05 to 0.10	6.4	96.5	6.1	97.5	2.7	97.3	7.7	96.1
0.11 to 0.24	2.5	99.0	2.0	99.5	1.9	99.2	2.9	99.0
0.25 to 0.49	1.0	100.0	0.5	100.0	0.8	100.0	1.0	100.0
N	515		198		520		208	

Forecast Categories (inch)	Percent Distribution of Forecasts			
0.0	84.7	79.3	80.4	66.4
0.01 to 0.04	1.2	0.0	11.0	13.0
0.05 to 0.09	1.7	0.5	2.9	6.7
0.10 to 0.19	7.0	14.6	2.5	7.2
0.20 to 0.29	3.7	4.6	1.7	4.3
0.30 to 0.99	1.7	1.0	1.5	2.4

* Percent (%)

** Cumulative Percent (Cum %)

Table B10. Percent and cumulative percent error of 60-minute forecasts for north and central sections.

Error (inch)	Man-Machine June-July		Man-Machine August		Objective June-July		Objective August	
	%*	Cum %**	%	Cum %	%	Cum %	%	Cum %
-0.99 to -0.50	0.2	0.2	0.6	0.6	0.4	0.4	0.0	0.0
-0.49 to -0.25	0.4	0.6	1.6	2.2	0.2	0.6	1.1	1.1
-0.24 to -0.11	1.3	1.9	2.2	4.4	2.1	2.7	1.6	2.7
-0.10 to -0.05	2.7	4.6	7.7	12.1	3.7	6.4	4.7	7.4
-0.04 to -0.01	12.4	17.0	19.2	31.3	12.3	18.7	19.5	26.9
0.0	66.5	83.5	46.7	78.0	64.4	83.1	44.7	71.6
0.01 to 0.04	3.3	86.8	3.3	81.3	7.8	90.9	10.5	82.1
0.05 to 0.10	7.0	93.8	13.2	94.5	3.1	94.0	4.2	86.3
0.11 to 0.24	3.7	97.5	4.9	99.4	3.3	97.3	9.5	95.8
0.25 to 0.49	2.1	99.6	0.6	100.0	1.9	99.2	3.7	99.5
0.50 to 0.99	0.4	100.0	0.0	100.0	0.8	100.0	0.5	100.0
N	484		182		486		190	

Forecast Categories (inch)	Percent Distribution of Forecasts			
0.0	80.4	68.7	74.1	55.3
0.01 to 0.04	1.2	0.0	11.7	16.3
0.05 to 0.09	1.4	0.6	4.5	5.3
0.10 to 0.19	7.9	15.4	3.9	7.9
0.20 to 0.29	3.1	9.3	1.1	6.8
0.30 to 0.99	5.8	6.0	4.3	8.4
≥1.0	0.2	0.0	0.4	0.0

* Percent (%)

** Cumulative Percent (Cum %)

Table B11. Percent and cumulative percent error of 120-minute forecasts for north and central sections.

Error (inch)	Man-Machine June-July		Man-Machine August		Objective June-July		Objective August	
	%*	Cum %**	%	Cum %	%	Cum %	%	Cum %
≥-1.00	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0
-0.99 to -0.50	1.4	1.4	2.6	2.6	0.9	1.2	2.5	2.5
-0.49 to -0.25	3.1	4.5	4.5	7.1	1.4	2.6	1.9	4.4
-0.24 to -0.11	5.5	10.0	7.8	14.9	5.0	7.6	8.2	12.6
-0.10 to -0.05	7.4	17.4	12.3	27.2	7.6	15.2	10.1	22.7
-0.04 to -0.01	4.3	21.7	20.0	47.2	13.9	29.1	17.7	40.4
0.0	52.1	73.8	27.7	74.9	48.3	77.4	23.4	63.8
0.01 to 0.04	16.1	89.9	4.5	79.4	9.4	86.8	13.3	77.1
0.05 to 0.10	4.3	94.2	13.5	92.9	3.5	90.3	7.0	84.1
0.11 to 0.24	4.0	98.2	5.8	98.7	3.5	93.8	7.6	91.7
0.25 to 0.49	0.9	99.1	1.3	100.0	3.8	97.6	3.8	95.5
0.50 to 0.99	0.9	100.0	0,0	100.0	2.4	100.0	3.8	99.3
≥1.0	0.0	100.0	0,0	100.0	0.0	100.0	0.7	100.0
N	422		155		424		158	

Forecast Categories (inch)	Percent Distribution of Forecasts			
0.0	70.1	54.2	65.3	44.3
0.01 to 0.04	2.1	1.3	12.0	12.7
0.05 to 0.09	1.9	0.7	6.6	9.5
0.10 to 0.19	11.9	21.9	4.5	10.1
0.20 to 0.29	3.1	7.7	3.5	8.2
0.30 to 0.99	9.7	14.2	6.7	13.3
≥1.00	1.2	0.0	1.4	1.9

* Percent (%)

** Cumulative Percent (Cum %)

Table B12. Percent of man-machine and objective forecast errors >0.1 inch for north and central sections in June-July and August.

Forecast Categories (Inch)	Man-Machine				Objective			
	June-July		August		June-July		August	
	N	%	N	%	N	%	N	%
30 Minutes								
0	436	0.2	157	0.0	418	0.2	138	0.0
0.01-0.09	15	0.0	1	0.0	72	1.4	41	0.0
0.10-0.19	36	2.7	29	6.9	13	15.4	15	13.3
0.20-0.29	19	68.4	9	66.7	9	88.9	9	44.4
0.30-0.99	9	100.0	2	50.0	8	87.5	5	60.0
60 Minutes								
0	389	0.3	125	3.2	360	0.8	105	2.9
0.01-0.09	13	0.0	1	0.0	79	5.1	41	2.4
0.10-0.19	38	10.5	28	7.1	9	47.4	15	33.3
0.20-0.29	15	46.7	17	23.5	5	80.0	13	61.5
0.30-0.99	28	92.9	11	72.7	2	95.2	16	87.5
≥1.0	1	100.0	0	0.0	2	100.0	0	0.0
120 Minutes								
0	296	3.4	84	15.5	277	6.5	70	17.1
0.01-0.09	17	5.9	3	66.7	79	10.1	35	8.6
0.10-0.19	50	16.0	32	15.6	19	36.8	16	43.8
0.20-0.29	13	76.9	12	50.0	15	53.3	13	38.4
0.30-0.99	41	80.4	22	36.4	28	92.8	21	71.4
≥1.0	5	100.0	0	0.0	6	100.0	3	100.0

Table B13. Percent of objective and man-machine forecasts with <50% error for north and central sections during June-July and August.

Forecast Categories (inch)	Man-Machine				Objective			
	June-July		August		June-July		August	
	N	%	N	%	N	%	N	%
30 Minutes								
0	436	86.9	157	75.1	418	88.7	138	85.5
0.01-0.09	15	20.0	1	100.0	72	27.8	41	31.7
0.10-0.19	36	22.2	29	48.3	13	23.1	15	33.3
0.20-0.29	19	26.3	9	22.2	9	33.3	9	55.6
0.30-0.99	9	11.1	2	0.0	8	12.5	5	40.0
60 Minutes								
0	389	82.5	125	67.2	360	85.0	105	77.1
0.01-0.09	13	30.8	1	100.0	79	21.5	41	31.7
0.10-0.19	38	15.8	28	32.1	19	36.8	15	40.0
0.20-0.29	15	20.0	17	47.1	5	20.0	13	30.8
0.30-0.99	28	21.4	11	45.5	21	19.0	16	31.2
≥1.0	1	100.0	0	0	2	0.0	0	0
120 Minutes								
0	296	71.6	84	47.6	277	71.1	70	50.0
0.01-0.09	17	35.3	3	33.3	79	22.8	35	28.6
0.10-0.19	50	32.0	34	32.4	19	31.6	16	37.5
0.20-0.29	13	15.4	12	58.3	15	33.3	31	53.8
0.30-0.99	41	36.6	22	77.3	28	21.4	21	47.6
:>1.0	5	40.0	0	0	6	16.7	3	0.0

Table B14. Frequency distribution of errors in man-machine accumulative forecasts for north and central sections during June-July.

Forecast Categories (Inch)	N	N_p		30-Minute Forecast Error (Inch)						N	N_p		60-Minute Forecast Error (Inch)						N	N_p		120-Minute Forecast Error (Inch)					
				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0
0.0	201	173	-	28	0	0	0	0	0	186	150	-	34	2	0	0	0	0	152	106	-	38	5	3	0	0	0
0.01-0.04	1	1	+	0	0	0	0	0	0	0	0	+	0	0	0	0	0	0	4	3	+	1	0	0	0	0	0
			-	0	0	0	0	0	0			-	0	0	0	0	0	0			-	0	0	0	0	0	0
0.05-0.09	4	0	+	2	2	0	0	0	0	4	0	+	3	1	0	0	0	0	4	0	+	0	3	0	0	0	0
			-	0	0	0	0	0	0			-	0	0	0	0	0	0			-	0	0	0	1	0	0
0.10-0.19	90	0	+	4	78	7	0	0	0	87	0	+	6	71	7	0	0	0	84	1	+	7	59	7	0	0	0
			-	1	0	0	0	0	0			-	1	2	0	0	0	0			-	5	1	2	1	1	0
0.20-0.29	36	1	+	17	3	14	0	0	0	33	2	+	13	3	14	0	0	0	29	3	+	13	4	8	0	0	0
			-	0	1	0	0	0	0			-	0	0	1	0	0	0			-	0	1	0	0	0	0
0.30-0.49	40	0	+	1	11	16	3	0	0	36	0	+	1	10	18	1	0	0	32	0	+	3	11	11	2	0	0
			-	0	1	8	0	0	0			-	0	0	5	1	0	0			-	0	0	5	0	0	0
0.50-0.74	41	0	+	0	0	14	17	5	0	38	0	+	0	0	10	15	5	0	30	0	+	0	2	3	12	5	0
			-	0	1	3	1	0	0			-	1	2	4	1	0	0			-	0	0	4	2	2	0
0.75-0.99	28	3	+	0	0	7	7	11	0	28	2	+	0	0	6	7	12	0	20	0	+	0	0	3	5	12	0
			-	0	0	0	0	0	0			-	0	0	0	0	1	0			-	0	0	0	0	0	0
1.00-1.49	56	0	+	0	0	6	0	27	16	56	0	+	0	0	5	1	28	16	51	0	+	0	0	2	3	30	10
			-	0	0	6	1	0	0			-	1	0	5	0	0	0			-	1	0	4	1	0	0
≥1.5	16	0	+	0	0	0	1	8	7	14	0	+	0	0	0	0	8	6	14	0	+	0	0	0	1	5	8
			-	0	0	0	0	0	0			-	0	0	0	0	0	0			-	0	0	0	0	0	0
TOTAL	513	178	+	24	94	64	28	51	23	482	154	+	23	85	60	24	53	22	420	113	+	24	79	34	23	52	18
			-	29	3	17	2	0	0			-	37	6	15	2	1	0			-	44	7	18	5	3	0

Table B15. Frequency distribution of errors in man-machine accumulative forecasts and rainfall for north and central sections during August.

Forecast Categories (Inch)	N	N_p		30-Minute Forecast Error (Inch) 0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0
0.0	66	48	-	17	1	0	0	0	0
0.01-0.04	0	0	+	0	0	0	0	0	0
			-	0	0	0	0	0	0
0.05-0.09	0	0	+	0	0	0	0	0	0
			-	0	0	0	0	0	0
0.10-0.19	22	1	+	4	11	0	0	0	0
			-	6	0	0	0	0	0
0.20-0.29	22	0	+	1	6	8	0	0	0
			-	0	6	0	1	0	0
0.30-0.49	15	0	+	2	3	3	1	0	0
			-	6	0	0	0	0	0
0.50-0.74	46	3	+	8	5	3	8	4	0
			-	3	5	3	4	0	0
0.75-0.99	3	0	+	0	0	0	0	0	0
			-	0	0	1	1	1	0
1.00-1.49	24	0	+	0	0	14	3	0	0
			-	0	0	0	6	1	0
TOTAL	198	52	+	15	25	28	12	4	0
			-	32	12	4	12	2	0

Forecast Categories (Inch)	N	N_p		60-Minute Forecast Error (Inch) 0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0
0.0	55	35	-	15	3	2	0	0	0
0.01-0.04	0	0	+	0	0	0	0	0	0
			-	0	0	0	0	0	0
0.05-0.09	0	0	+	0	0	0	0	0	0
			-	0	0	0	0	0	0
0.10-0.19	19	0	+	2	10	0	0	0	0
			-	6	0	0	0	1	0
0.20-0.29	21	0	+	1	6	8	0	0	0
			-	0	6	0	0	0	0
0.30-0.49	17	1	+	2	2	6	1	0	0
			-	5	0	0	0	0	0
0.50-0.74	39	2	+	5	5	5	5	3	0
			-	4	2	5	2	1	0
0.75-0.99	9	0	+	4	0	0	1	1	0
			-	0	0	1	0	2	0
1.00-1.49	22	0	+	0	0	14	2	0	0
			-	0	0	0	6	0	0
TOTAL	182	38	+	14	23	33	9	4	0
			-	30	11	8	8	4	0

Forecast Categories (Inch)	N	N_p		120-Minute Forecast Error (Inch) 0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0
0.0	40	18	-	12	2	6	1	1	0
0.01-0.04	2	0	+	0	0	0	0	0	0
			-	0	0	1	1	0	0
0.05-0.09	0	0	+	0	0	0	0	0	0
			-	0	0	0	0	0	0
0.10-0.19	19	0	+	1	8	2	0	0	0
			-	7	0	0	0	1	0
0.20-0.29	14	0	+	0	3	5	0	0	0
			-	0	4	2	0	0	0
0.30-0.49	17	1	+	1	3	5	1	0	0
			-	4	2	0	0	0	0
0.50-0.74	34	1	+	5	5	5	3	1	0
			-	1	7	2	2	2	0
0.75-0.99	10	0	+	2	0	3	1	1	0
			-	0	0	1	0	2	0
1.00-1.49	19	0	+	0	0	13	1	0	0
			-	0	0	0	4	1	0
TOTAL	155	20	+	9	19	33	6	2	0
			-	24	15	12	8	7	0

Table B16. Frequency distribution of percent error of accumulated man-machine forecasts for north and central sections during June-July.

Forecast (Inch)

	0.0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.49	0.50- 0.74	0.75- 0.99	1.00- 1.49	≥ 1.5	Total
30-Minutes											
∞		0	1	19	0	0	0	0	0	0	20
≥500		0	1	23	8	0	2	0	0	0	34
100 to 499		0	1	42	7	18	20	12	43	14	157
50 to 99		0	1	3	1	8	8	6	0	1	28
20 to 49		0	0	1	3	3	6	7	6	1	27
1 to 19		0	0	1	15	2	0	0	0	0	18
0	173	1	0	0	1	0	0	3	0	0	178
-1 to -19		0	0	-0	0	0	4	0	7	0	11
-20 to -49		0	0	1	1	9	1	0	0	0	12
-50 to -69		0	0	0	0	0	0	0	0	0	0
-70 to -99		0	0	0	0	0	0	0	0	0	0
-100	28										28
Total	201	1	4	90	36	40	41	28	56	16	513
60-Minutes											
∞		0	0	17	2	0	0	0	0	0	19
≥500		0	1	19	7	0	1	1	0	0	29
100 to 499		0	2	40	6	15	18	11	44	12	148
50 to 99		0	0	4	2	9	7	7	1	1	31
20 to 49		0	0	3	0	5	4	6	5	1	24
1 to 19		0	1	1	13	1	0	0	0	0	16
0	150	0	0	0	2	0	0	2	0	0	154
-1 to -19		0	0	0	0	0	6	0	6	0	12
-20 to -49		0	0	3	1	5	2	1	0	0	12
-50 to -69		0	0	0	0	1	0	0	0	0	1
-70 to -99		0	0	0	0	0	0	0	0	0	0
-100	36										
Total	186		4	87	33	36	38	28	56	14	482
120-Minutes											
∞		1	2	13	0	2	0	0	0	0	18
≥500		0	0	17	5	0	0	0	0	0	22
100 to 499		0	1	35	5	8	16	13	39	11	128
50 to 99		0	0	3	1	7	2	4	2	2	21
20 to 49		0	0	3	1	4	2	3	4	1	18
1 to 19		0	0	2	13	6	2	0	0	0	23
0	106	3	0	1	3	0	0	0	0	0	113
-1 to -19		0	0	3	0	0	3	0	5	0	11
-20 to -49		0	0	3	1	5	3	0	1	0	13
-50 to -69		0	0	2	0	0	2	0	0	0	4
-70 to -99		0	1	2	0	0	0	0	0	0	3
-100	46										46
Total	152	4	4	84	29	32	30	20	51	14	420

Table B17. Frequency distribution of percent error of accumulated man-machine forecasts for north and central sections during August.

Forecast (Inch)

	0.0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.49	0.50- 0.74	0.75- 0.99	1.00- 1.49	Total
					30-Minutes					
∞		0	0	9	1	0	0	0	0	10
≥500		0	0	1	0	0	4	0	0	5
100 to 499		0	0	1	7	3	6	0	0	17
50 to 99		0	0	2	5	0	2	0	0	9
20 to 49		0	0	1	1	3	4	0	17	26
1 to 19		0	0	1	1	3	12	0	0	17
0	48	0	0	1	0	0	3	0	0	52
-1 to -19		0	0	4	0	6	9	1	0	20
-20 to -49		0	0	2	6	0	6	2	7	23
-50 to -69		0	0	0	1	0	0	0	0	1
-70 to -99		0	0	0	0	0	0	0	0	0
-100	18									18
Total	66			22	22	15	46	3	24	198
					60-Minutes					
∞		0	0	7	2	0	0	0	0	9
≥500		0	0	0	0	0	3	0	0	3
100 to 499		0	0	3	6	4	4	1	0	18
50 to 99		0	0	1	5	2	2	1	0	11
20 to 49		0	0	0	1	2	5	0	15	23
1 to 19		0	0	1	1	3	9	4	1	19
0	35	0	0	0	0	1	2	0	0	38
-1 to -19		0	0	3	0	5	8	1	0	17
-20 to -49		0	0	3	6	0	6	2	6	23
-50 to -69		0	0	0	0	0	0	0	0	0
-70 to -99		0	0	1	0	0	0	0	0	1
-100	20									20
Total	55			19	21	17	39	9	22	182
					120-Minutes					
∞		0	0	5	1	0	0	0	0	6
≥500		0	0	1	1	0	1	0	0	3
100 to 499		0	0	4	3	4	3	1	0	15
50 to 99		0	0	0	3	0	0	1	0	4
20 to 49		0	0	0	0	4	3	1	12	20
1 to 19		0	0	1	0	2	12	4	2	21
0	18	0	0	0	0	1	1	0	0	20
-1 to -19		0	0	3	0	5	9	1	0	18
-20 to -49		0	0	4	5	1	4	2	5	21
-50 to -69		0	0	0	1	0	1	0	0	2
-70 to -99		2	0	1	0	0	0	0	0	3
-100	22									22
Total	40	2		19	14	17	34	10	19	155

Table B18. Frequency distribution of errors in objective accumulated forecasts and rainfall for north and central sections during June-July.

Forecast Categories (Inch)	N	N_p		30-Minute Forecast Error (Inch)						N	N_p		60-Minute Forecast Error (Inch)						N	N_p		120-Minute Forecast Error (Inch)					
				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0				0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0
0.0	45	43	-	2	0	0	0	0	0	42	38	-	4	0	0	0	0	0	41	32	-	8	1	0	0	0	0
0.01-0.04	125	1	+	123	0	0	0	0	0	116	2	+	110	0	0	0	0	0	88	3	+	74	0	0	0	0	0
			-	1	0	0	0	0	0			-	4	0	0	0	0	0			-	3	5	2	0	1	0
0.05-0.09	73	1	+	10	58	0	0	0	0	65	1	+	11	46	0	0	0	0	60	0	+	12	37	0	0	0	0
			-	1	2	1	0	0	0			-	2	4	1	0	0	0			-	1	2	3	4	0	1
0.10-0.19	43	0	+	0	14	28	0	0	0	42	1	+	2	13	24	0	0	0	42	2	+	2	14	17	0	0	0
			-	0	0	0	1	0	0			-	0	0	1	1	0	0			-	0	4	1	1	1	0
0.20-0.29	39	0	+	0	3	28	0	0	0	38	0	+	2	4	26	0	0	0	34	0	+	1	6	21	2	0	0
			-	1	2	0	5	0	0			-	1	1	0	4	0	0			-	2	0	0	2	0	0
0.30-0.49	46	0	+	0	1	36	7	0	0	40	0	+	0	2	31	5	0	0	31	0	+	1	2	21	5	0	0
			-	0	0	2	0	0	0			-	0	1	0	1	0	0			-	1	0	1	0	0	0
0.50-0.74	47	0	+	1	0	4	32	6	0	42	0	+	1	0	3	30	4	0	37	1	+	1	2	2	24	2	0
			-	0	1	3	0	0	0			-	0	1	2	1	0	0			-	0	1	2	0	2	0
0.75-0.99	26	0	+	0	0	7	5	10	0	26	0	+	0	0	5	5	11	0	21	0	+	0	0	3	4	13	0
			-	4	0	0	0	0	0			-	4	0	0	0	1	0			-	1	0	0	0	0	0
1.00-1.49	56	0	+	0	0	0	0	32	17	57	0	+	0	0	0	0	35	16	55	0	+	0	0	0	1	31	18
			-	0	0	6	1	0	0			-	1	0	4	1	0	0			-	1	0	3	1	0	0
≥1.50	20	0	+	0	0	0	0	8	12	18	0	+	0	0	0	0	5	13	15	0	+	0	0	0	0	4	11
			-	0	0	0	0	0	0			-	0	0	0	0	0	0			-	0	0	0	0	0	0
TOTAL	520	45	+	134	76	103	44	56	29	486	42	+	126	65	89	40	55	29	424	38	+	91	61	64	36	50	29
			-	9	5	12	7	0	0			-	16	7	8	8	1	0			-	17	13	12	8	4	1

Table B19. Frequency distribution of errors in objective accumulated forecasts and rainfall for north and central sections during August.

Forecast Categories (Inch)				30-Minute Forecast Error (Inch)									60-Minute Forecast Error (Inch)									120-Minute Forecast Error (Inch)					
	N	N_p		0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0	N	N_p		0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0	N	N_p		0.01-0.04	0.05-0.10	0.11-0.24	0.25-0.49	0.50-0.99	≥1.0
0.0	8	8	-	0	0	0	0	0	0	6	4	-	0	0	2	0	0	0	6	0	-	0	0	6	0	0	0
0.01-0.04	28	0	+	23	0	0	0	0	0	23	0	+	18	0	0	0	0	0	15	1	+	12	0	0	0	0	0
			-	0	5	0	0	0	0			-	1	4	0	0	0	0			-	0	1	0	1	0	0
0.05-0.09	24	0	+	1	23	0	0	0	0	20	0	+	0	19	0	0	0	0	14	0	+	1	13	0	0	0	0
			-	0	0	0	0	0	0			-	1	0	0	0	0	0			-	0	0	0	0	0	0
0.10-0.19	19	0	+	4	4	10	0	0	0	17	0	+	3	1	12	0	0	0	13	0	+	4	3	5	0	0	0
			-	1	0	0	0	0	0			-	1	0	0	0	0	0			-	1	0	0	0	0	0
0.20-0.29	25	0	+	1	4	19	1	0	0	21	1	+	1	3	14	2	0	0	15	0	+	0	2	10	0	0	0
			-	0	0	0	0	0	0			-	0	0	0	0	0	0			-	0	1	1	1	0	0
0.30-0.49	10	0	+	0	0	3	7	0	0	12	0	+	0	1	3	7	0	0	13	0	+	0	1	2	7	0	0
			-	0	0	0	0	0	0			-	0	0	0	1	0	0			-	2	0	0	0	1	0
0.50-0.74	17	0	+	1	0	2	13	1	0	18	0	+	0	0	2	14	1	0	17	0	+	0	1	3	10	1	0
			-	0	0	0	0	0	0			-	0	0	1	0	0	0			-	0	1	0	1	0	0
0.75-0.99	27	0	+	0	0	3	10	14	0	26	0	+	0	0	0	13	13	0	25	0	+	0	0	5	11	9	0
			-	0	0	0	0	0	0			-	0	0	0	0	0	0			-	0	0	0	0	0	0
1.00-1.49	25	0	+	0	0	0	8	14	2	20	0	+	0	0	2	9	8	1	15	0	+	0	0	2	7	5	1
			-	1	0	0	0	0	0			-	0	0	0	0	0	0			-	0	0	0	0	0	0
≥1.50	25	0	+	0	0	0	0	24	1	27	0	+	0	0	0	1	24	2	25	0	+	0	1	1	1	20	2
			-	0	0	0	0	0	0			-	0	0	0	0	0	0			-	0	0	0	0	0	0
TOTAL	208	8	+	30	31	37	39	53	3	190	5	+	22	24	33	46	46	3	158	1	+	17	21	28	36	35	3
			-	2	5	0	0	0	0			-	3	4	3	1	0	0			-	3	3	7	3	1	0

Table B20. Frequency of percent error of objective accumulated forecast for north and central sections during June-July.

Forecast (Inch)

	0.0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.49	0.50- 0.74	0.75- 0.99	1.00- 1.49	≥1.5	Total
30-Minutes											
∞		107	34	8	0	0	0	0	0	0	149
≥500		0	18	10	7	0	1	0	0	6	42
100 to 499		14	13	20	20	28	36	10	49	6	196
50 to 99		2	1	4	3	13	5	5	0	8	41
20 to 49		0	2	0	1	3	0	1	0	0	7
1 to 19		0	0	0	0	0	1	6	0	0	7
0	43	1	1	0	0	0	0	0	0	0	45
-1 to -19		0	0	0	2	0	3	4	7	0	16
-20 to -49		0	2	0	4	2	1	0	0	0	9
-50 to -69		1	2	0	2	0	0	0	0	0	5
-70 to -99			0	1	0	0	0	0	0	0	1
-100	2	0									2
Total	45	125	73	43	39	46	47	26	56	20	520
60-Minutes											
∞		94	28	8	0	0	0	0	0	0	130
≥500		0	15	9	6	0	0	0	1	5	36
100 to 499		15	11	19	18	24	33	11	50	6	187
50 to 99		1	1	1	5	11	4	5	0	7	35
20 to 49		0	2	2	1	3	0	1	0	0	9
1 to 19		0	0	0	2	0	1	4	0	0	7
0	38	2	1	1	0	0	0	0	0	0	42
-1 to -19		0	1	0	1	1	2	4	6	0	15
-20 to -49		0	3	1	3	0	2	1	0	0	10
-50 to -69		3	3	0	2	1	0	0	0	0	9
-70 to -99		1	0	1	0	0	0	0	0	0	2
-100	4										4
Total	42	116	65	42	38	40	42	26	57	18	486
120-Minutes											
∞		62	22	4	2	0	0	0	0	0	90
≥500		0	11	6	5	0	0	0	0	3	25
100 to 499		12	13	18	15	19	25	15	49	8	174
50 to 99		0	0	2	4	6	2	2	0	4	20
20 to 49		0	1	2	3	2	1	1	1	0	11
1 to 19		0	2	1	1	2	3	2	0	0	11
0	32	3	0	2	0	0	1	0	0	0	38
-1 to -19		0	1	0	2	1	2	1	5	0	12
-20 to -49		0	1	5	0	1	1	0	0	0	8
-50 to -69		3	3	0	2	0	2	0	0	0	10
-70 to -99		8	6	2	0	0	0	0	0	0	16
-100	9										9
Total	41	88	60	42	34	31	37	21	55	15	424

Table B21. Frequency of percent error of objective accumulated forecast for north and central sections during August.

Forecast (Inch)

	0.0	0.01- 0.04	0.05- 0.09	0.10- 0.19	0.20- 0.29	0.30- 0.49	0.50- 0.74	0.75- 0.99	1.00- 1.49	≥1.5	Total
						30-Minutes					
∞		23	23	4	0	1	0	0	0	0	51
≥500		0	0	6	11	1	0	3	1	0	22
100 to 499		0	1	1	9	8	5	11	3	1	39
50 to 99		0	0	4	4	0	11	10	19	23	71
20 to 49		0	0	2	0	0	0	3	1	1	7
1 to 19		0	0	1	1	0	1	0	0	0	3
0	8	0	0	0	0	0	0	0	0	0	8
-1 to -19		0	0	1	0	0	0	0	1	0	2
-20 to -49		0	0	0	0	0	0	0	0	0	0
-50 to -69		0	0	0	0	0	0	0	0	0	0
-70 to -99		5	0	0	0	0	0	0	0	0	0
-100											5
Total	8	28	24	19	25	10	17	27	25	25	208
						60-Minutes					
∞		18	18	5	0	0	0	0	0	0	41
≥500		0	0	7	8	2	0	3	0	0	20
100 to 499		0	1	1	8	7	7	11	1	2	38
50 to 99		0	0	0	3	0	9	10	13	23	58
20 to 49		0	0	2	0	2	1	2	5	2	14
1 to 19		0	0	1	1	0	0	0	1	0	3
0	4	0	0	0	1	0	0	0	0	0	5
-1 to -19		0	1	0	0	0	0	0	0	0	1
-20 to -49		0	0	1	0	1	1	0	0	0	3
-50 to -69		2	0	0	0	0	0	0	0	0	2
-70 to -99		3	0	0	0	0	0	0	0	0	3
-100	2										2
Total	6	23	20	17	21	12	18	26	20	27	190
						120-Minutes					
∞		11	12	2	0	0	0	0	0	0	25
≥500		0	0	5	4	4	0	1	1	0	15
100 to 499		0	2	1	6	5	6	9	1	3	33
50 to 99		1	0	0	1	0	6	7	7	18	40
20 to 49		0	0	2	1	0	2	7	5	2	19
1 to 19		0	0	2	0	1	1	1	1	2	8
0		1	0	0	0	0	0	0	0	0	1
-1 to -19		0	0	0	0	2	1	0	0	0	3
-20 to -49		0	0	1	2	0	1	0	0	0	4
-50 to -69		0	0	0	1	1	0	0	0	0	2
-70 to -99		2	0	0	0	0	0	0	0	0	2
-100	6										6
Total	6	15	14	13	15	13	17	25	15	25	158

Table B22. Percent and cumulative percent error for 30-minutes accumulated forecasts over north and central sections.

	Man-Machine				Objective			
	June-July		August		June-July		August	
Error (Inch)	%*	Cum %***	%	Cum %	%	Cum %	%	Cum %
-0.50 to -0.99	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0
-0.25 to -0.49	0.4	0.4	6.0	7.0	1.3	1.3	0.0	0.0
-0.11 to -0.24	3.3	3.7	2.0	9.0	2.3	3.6	0.0	0.0
-0.05 to -0.10	0.6	4.3	6.1	15.1	1.0	4.6	2.4	2.4
-0.01 to -0.04	5.6	9.9	16.2	31.3	1.7	6.3	1.0	3.4
0	34.7	44.6	26.3	57.6	8.7	15.0	3.8	7.2
0.01 to 0.04	4.7	49.3	7.6	65.2	25.7	40.7	14.4	21.6
0.05 to 0.10	18.3	67.6	12.6	77.8	14.6	55.3	14.9	36.5
0.11 to 0.24	12.5	80.1	14.1	91.9	19.8	75.1	17.8	54.3
0.25 to 0.49	5.5	85.6	6.1	98.0	8.5	83.6	18.8	73.1
0.50 to 0.99	9.9	95.5	2.0	100.0	10.8	94.4	25.5	98.6
≥ 1.00	4.5	100.0	0.0	100.0	5.6	100.0	1.4	100.0
N	513		198		520		208	

Percent distribution of forecasts

Forecast Category (Inch)				
0.0	39.2	33.3	8.7	3.8
0.01 to 0.04	0.2	0.0	24.0	13.5
0.05 to 0.09	0.8	0.0	14.0	11.6
0.10 to 0.19	17.5	11.1	8.3	9.1
0.20 to 0.29	7.0	11.1	7.5	12.0
0.30 to 0.49	7.8	7.6	8.9	4.8
0.50 to 0.74	8.0	23.3	9.0	8.2
0.75 to 0.99	5.5	1.5	5.0	13.0
1.00 to 1.49	10.9	12.1	10.8	12.0
≥ 1.50	3.1	0.0	3.8	12.0

* Percent (%)

** Cumulative Percent (Cum %)

Table B23. Percent and cumulative percent error for 60-minute accumulated rain forecasts over north and central sections.

	Man-Machine				Objective			
	June-July		August		June-July		August	
Error (Inch)	%*	Cum %**	%	Cum %	%	Cum %	%	Cum %
-0.50 to -0.99	0.2	0.2	2.2	2.2	0.2	0.2	0.0	0.0
-0.25 to -0.49	0.4	0.6	4.4	6.6	1.7	1.9	0.5	0.5
-0.11 to -0.25	3.1	3.7	4.4	11.0	1.7	3.6	1.6	2.1
-0.05 to -0.10	1.2	4.9	6.0	17.0	1.4	5.0	2.1	4.2
-0.01 to -0.04	7.7	12.6	16.5	33.5	3.3	8.3	1.6	5.8
0	32.0	44.6	20.9	54.4	8.6	16.9	2.6	8.4
0.01 to 0.04	4.8	49.4	7.7	62.1	25.9	42.8	11.6	20.0
0.05 to 0.10	17.6	67.0	12.6	74.7	13.4	56.2	12.6	32.6
0.11 to 0.24	12.4	79.4	18.1	92.8	18.3	74.5	17.4	50.0
0.25 to 0.49	5.0	84.4	5.0	97.8	8.2	82.7	24.2	74.2
0.50 to 0.99	11.0	95.4	2.2	100.0	11.3	94.0	24.2	98.4
≥ 1.00	4.6	100.0	0.0	100.0	6.0	100.0	1.6	100.0
N	482		182		486		190	

Percent distribution of forecasts

Forecast Category (Inch)				
0.0	38.6	30.2	8.6	3.2
0.01 to 0.04	0.0	0.0	23.9	12.1
0.05 to 0.09	0.8	0.0	13.4	10.5
0.10 to 0.19	18.1	10.4	8.7	8.9
0.20 to 0.29	6.8	11.6	7.8	11.1
0.30 to 0.49	7.5	9.3	8.2	6.3
0.50 to 0.74	7.9	21.4	8.6	9.5
0.75 to 0.99	5.8	5.0	5.4	13.7
1.00 to 1.49	11.6	12.1	11.7	10.5
≥ 1.50	2.9	0.0	3.7	14.2

* Percent (%)

** Cumulative Percent (Cum %)

Table B24. Percent and cumulative percent error for 120-minutes accumulative forecasts over north and central sections.

	Man-Machine				**Objective**			
	June-July		**August**		**June-July**		**August**	
Error (Inch)	**%***	**Cum %****	**%**	**Cum %**	**%**	**Cum %**	**%**	**Cum %**
≤ 1.00	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0
-0.50 to -0.99	0.7	0.7	4.5	4.5	0.9	1.1	0.6	0.6
-0.25 to -0.49	1.2	1.9	5.2	9.7	1.9	3.0	1.9	2.5
-0.11 to -0.24	4.3	6.2	7.7	17.4	2.8	5.8	4.4	6.9
-0.05 to -0.10	1.7	7.9	9.7	27.1	3.1	8.9	1.9	8.8
-0.01 to -0.04	10.5	18.4	15.5	42.6	4.0	12.9	1.9	10.7
0	26.9	45.3	12.9	55.5	9.0	21.9	0.6	11.3
0.01 to 0.04	5.7	51.0	5.8	61.3	21.5	43.4	10.8	22.1
0.05 to 0.10	18.8	69.8	12.2	73.5	14.4	57.8	13.3	35.4
0.11 to 0.24	8.1	77.9	21.3	94.8	15.1	72.9	17.7	53.1
0.25 to 0.49	5.5	83,4	3.9	98.7	8.5	81.4	22.8	75.9
0.05 to 0.99	12.3	95.7	1.3	100.0	11.8	93.2	22.2	98.1
≥ 1.00	4.3	100.0	0.0	100.0	6.8	100.0	1.9	100.0
N	420		155		424		158	

Percent Distribution of Forecasts

Forecast Category (Inch)	Man-Machine June-July	Man-Machine August	Objective June-July	Objective August
0.0	36.2	25.8	9.7	3.8
0.01 to 0.04	1.0	1.3	20.8	9.5
0.05 to 0.09	1.0	0.0	14.2	8.9
0.01 to 0.19	20.0	12.3	9.9	8.2
0.20 to 0.29	6.9	9.0	8.0	9.5
0.30 to 0.49	7.6	11.0	7.3	8.2
0.50 to 0.74	7.1	21.9	8.7	10.8
0.75 to 0.99	4.8	6.4	4.9	15.8
1.00 to 1.49	12.1	12.3	13.0	9.5
≥ 1.50	3.3	0.0	3.5	15.8

* Percent (%)

** Cumulative Percent (Cum %)

Table B25. Percent of objective and man-machine accumulated forecast errors > 0.1 inch for north and central sections in June-July and August.

Forecast Category (Inch)	Man-Machine				Objective			
	June-July		August		June-July		August	
	N	%	N	%	N	%	N	%
				30-minute				
0.0	201	0.0	66	0.0	45	0.0	8	0.0
0.01 to 0.04	1	0.0	0	0.0	125	0.0	28	0.0
0.05 to 0.09	4	0.0	0	0.0	73	1.4	24	0.0
0.10 to 0.19	90	7.8	22	0.0	43	67.4	19	52.6
0.20 to 0.29	36	38.9	22	40.9	39	84.6	25	80.0
0.30 to 0.49	40	67.5	15	26.7	46	97.8	10	100.0
0.50 to 0.74	41	97.6	46	47.8	47	95.7	17	94.1
0.75 to 0.99	28	100.0	3	100.0	26	84.6	27	100.0
1.00 to 1.49	56	100.0	24	100.0	56	100.0	25	96.0
≥ 1.50	16	100.0	0	0.0	20	100.0	25	100.0
				60-minute				
0.0	186	0.0	55	3.6	42	0.0	6	100.0
0.01 to 0.04	0	0.0	0	0.0	116	0.0	23	0.0
0.05 to 0.09	4	0,0	0	0.0	65	1.5	20	0.0
0.10 to 0.19	87	8.0	19	5.3	42	61.9	17	70.6
0.20 to 0.29	33	42.4	21	38.1	38	78.9	21	76.2
0.30 to 0.49	36	69.4	17	41.2	40	92.5	12	91.7
0.50 to 0.74	38	92.1	39	53.8	42	95.2	18	100.0
0.75 to 0.99	28	92.9	9	55.6	26	84.6	26	100.0
1.00 to 1.49	56	98.2	22	100.0	57	98.2	20	100.0
≥ 1.50	14	100.0	0	0.0	18	100.0	27	100.0
				120-minute				
0.0	152	2.0	40	20.0	41	0.0	6	100.0
0.01 to 0.04	4	0.0	2	100.0	88	3.4	15	6.7
0.05 to 0.09	4	25.0	0	0.0	60	11.7	14	0.0
0.10 to 0.19	84	13.1	19	15.8	42	47.6	13	38.5
0.20 to 0.29	29	27.6	14	50.0	34	80.6	15	80.0
0.30 to 0.49	32	53.1	17	35.3	31	87.1	13	76.9
0.50 to 0.74	30	93.3	34	44.1	37	86.5	17	88.2
0.75 to 0.99	20	100.0	10	80.0	21	95.2	25	100.0
1.00 to 1.49	51	98.0	19	100.0	55	98.2	15	100.0
≥ 1.50	14	100.0	0	0.0	15	100.0	25	96.0

Table B26. Percent of accumulated man-machine and objective forecasts with < 50% error for north and central sections during June-July and August.

Forecast Category (Inch)	Man-machine				Objective			
	June-July		August		June-July		August	
	N	%	N	%	N	%	N	%
				30-minute				
0.0	173	16.2	66	72.7	45	95.6	8	100.0
0.01 to 0.04	1	100.0	0	0.0	125	0.8	28	0.0
0.05 to 0.09	4	0.0	0	0.0	73	6.8	24	0.0
0.10 to 0.19	90	3.3	22	40.9	43	0.0	19	21.1
0.20 to 0.29	36	55.6	22	36.4	39	17.9	25	4.0
0.30 to 0.49	40	35.0	15	80.0	46	10.9	10	0.0
0.50 to 0.74	41	26.8	46	73.9	47	10.6	17	5.9
0.75 to 0.99	28	35.7	3	100.0	26	42.8	27	11.1
1.00 to 1.49	56	23.2	24	100.0	56	12.5	25	8.0
≥ 1.50	16	6.3	0	0.0	20	0.0	25	4.0
				60-minute				
0.0	186	80.7	55	63.6	42	90.5	6	66.7
0.01 to 0.04	0	0.0	0	0.0	116	1.7	23	0.0
0.05 to 0.09	4	25.0	0	0.0	65	10.8	20	5.0
0.10 to 0.19	87	12.6	19	36.8	42	9.5	17	23.5
0.20 to 0.29	33	55.6	21	38.1	38	18.4	21	9.5
0.30 to 0.49	36	30.6	17	64.7	40	10.0	12	25.0
0.50 to 0.74	38	31.6	39	76.9	42	11.9	18	11.1
0.75 to 0.99	28	32.1	9	77.8	26	38.5	26	7.7
1.00 to 1.49	56	19.6	22	100.0	57	10.5	20	30.0
≥ 1.50	14	7.1	0	0.0	18	0.0	27	7.4
				120-minute				
0.0	152	69.7	40	45.0	41	78.0	6	0.0
0.01 to 0.04	4	75.0	2	0.0	88	3.4	15	6.7
0.05 to 0.09	4	0.0	0	0.0	60	8.3	14	0.0
0.10 to 0.19	84	14.3	19	42.1	42	23.8	13	38.5
0.20 to 0.29	29	62.1	14	35.7	34	17.6	15	20.0
0.30 to 0.49	32	46.9	17	76.5	31	19.8	13	23.1
0.50 to 0.74	30	33.3	34	85.3	37	21.6	17	29.4
0.75 to 0.99	20	15.0	10	80.0	21	19.0	25	32.0
1.00 to 1.49	51	19.6	19	100.0	55	10.9	15	40.0
≥ 1.50	14	7.1	0	0.0	15	0.0	25	16.0