Atmospheric Sciences Section
Illinois State Water Survey

CHICAGO HYDROMETEOROLOGICAL AREA PROJECT: A COMPREHENSIVE NEW STUDY OF URBAN HYDROMETEOROLOGY

ANNUAL AND INTERIM REPORT

Annual Report for 1976
and
Progress Report for 1977

Program of Advanced Environmental Research and Technology-
Research Applied to National Needs
National Science Foundation

for

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and
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Principal Investigators

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ACKNOWLEDGMENTS

The success of the research accomplished to date is a credit to the many excellent contributions of the project staff.

Douglas M. A. Jones has supervised the siting, installation, and operation of the 320-gage network. He has been ably assisted in these tasks by Paul D. Lamb.

Dr. Eugene A. Mueller has directed the various engineering tasks in establishing the radar activities on the project, and has been a valuable in-house consultant on the radar data analyses. Donald W. Staggs supervised the building construction for the radar facility and installation of the primary radar system (FPS-18). He has also been supervisor of all radar operations, and responsible for maintenance of the system.

David A. Brunkow has contributed greatly in engineering tasks associated with the project, particularly in establishing the interfacing of radar, processors, and on-site computer. He has also been responsible for computer programs which are an integral part of the radar system operation and transfer of information to MSD. Herbert Yuen has been chief programmer in the analysis phase of the research, which includes the real-time adjustment of the radar rainfall field and for development of programs for tracking and prediction. Gregory Fetter has contributed to field operations and provided assistance in the development of the tracking and prediction programs.

Immediate supervision of the analyses of radar and rainfall data has been the responsibility of Neil G. Towery. Nancy Westcott has been active in various analysis tasks. John L. Vogel is functioning as program coordinator and supervisor of rainfall analyses for application in hydrologic design problems.

Arthur L. Sims has been responsible for developing the programs involved in processing of the raingage data. Phyllis Stone has supervised data editing and Leah Trover the machine processing of the raingage data. Various raingage technicians, radar operators, and data analysts have also contributed measureably to activities.

We also express our appreciation to Victor Wiggert of the NOAA/FACE project for furnishing us with their tracking program and for consultation in modifying it for our application. Dr. Amos Eddy has provided helpful consultation on the radar-rainfall data analysis and made available his computer programs for potential application in the real-time operations.

We are especially indebted to Dr. William C. Ackermann, Chief of the Water Survey, for his consultation and interactions with engineering and hydrologic users of the project data and findings. We also greatly appreciate the cooperation we have received from various outside agencies,

such as the Metropolitan Sanitary District of Greater Chicago, the Northeast Illinois Planning Commission, Chicago Department of Public Works, and the Cook County Forest Preserve District in establishing the field project, particularly the raingage network. Other individuals too numerous to mention provided assistance in various aspects of the planning and establishment of the research project.

INTRODUCTION

Background

In an effort to better describe the hydrometeorology of Chicago and environs, an investigative program was begun by Water Survey scientists in 1974. All the historical rainfall data for the area were procured and studied. The resulting analyses were aimed primarily at providing rainfall information of various types that would be useful to urban hydrologists in the design of storm-sanitary sewer systems. This investigation culminated in the publication of a Water Survey report (Huff and Vogel, 1976) which provided much useful information on various aspects of the hydrometeorology of heavy rainstorms in Chicago and northeastern Illinois. However, these results, plus interaction with various local and regional users in the Chicago area, revealed further extensive needs for a sophisticated level of urban rainfall data and information that could not be served by the results obtained from the existing data base at Chicago or those at most other major American cities.

To this end, the Illinois State Water Survey began designing and developing a comprehensive urban hydrometeorological investigation. Thus, an extensive rainfall measurement program, which became labeled as Phase 2, was planned. The study of the historical data done in 1974-1976 was labeled as Phase 1. It aimed at developing a short-term rainfall probability forecast skill, real-time estimates of rainfall over the city, rainfall information for water quality and runoff models, and extensive rainfall frequency data for the 10,000 km^2 area enveloping Chicago. This was envisioned as a 5-year project and it was launched in the fall of 1975 with funding from the State of Illinois. The National Science Foundation's Program for Research Applied to National Needs subsequently funded a portion of the program beginning in February 1976.

The major facilities of Phase 2 include the world's largest dense raingage network of over 320 recording raingages and a new sophisticated 10-cm weather radar with state-of-the-art signal processing and an attached computer that allow for rapid digitization of rainfall data. Simply, the radar-computer system is being linked with the Metropolitan Sanitary District Operational Headquarters to demonstrate, both locally and nationally, the use of a sophisticated weather radar system in the real-time operations of an urban hydrologic system. The raingage network furnishes rainfall data for calibrating the radar-indicated rainfall, for testing water quality models, for developing new rainstorm intensity models, and for studying localized effects (urban and lake) on rainfall.

This report, which is being prepared at the end of the 22nd month of NSF/RANN sponsorship, serves as an annual report for the first year, basically 1976, and a progress report for the first 10 months of the second year. It indicates the extent of the effort to date, the progress that has been made towards serving the project goals, the interesting findings already available, and the user interactions.

Goals

Phase 2 has the following major goals:

1. To develop a real-time prediction and monitoring system and methodology for specifying rainfall quantity over the urban area using a weather radar.

2. To provide precipitation data and information for hydrologic and water quality models and for use in the design of hydrologic systems.

3. To establish methods and techniques for transferring the Chicago area findings to other cities, so as to optimize precipitation measurement systems.

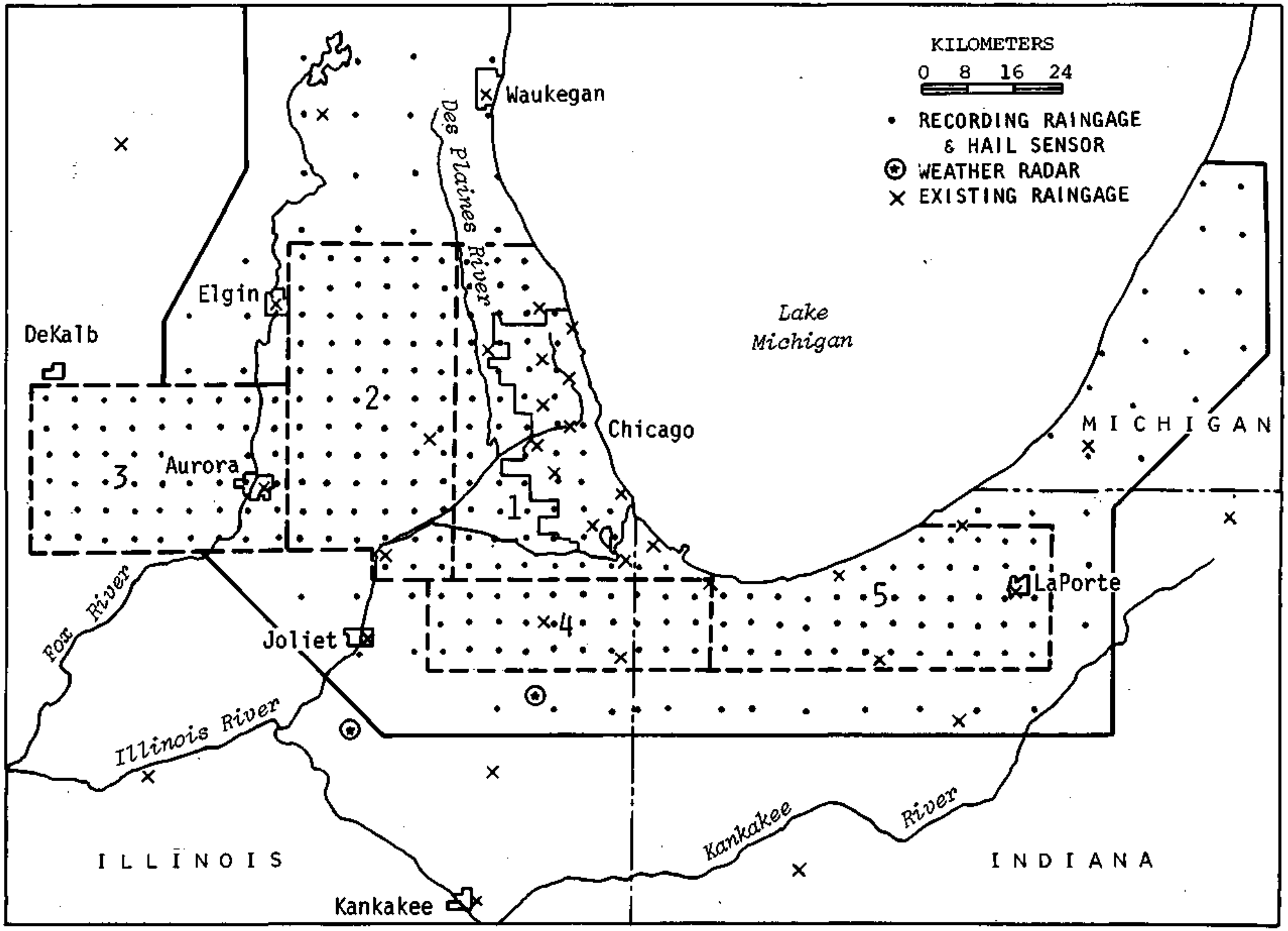
Objectives

There are specific objectives of the Chicago Hydrometeorological Area Project (CHAP). The first of these focuses on the development of better and more detailed rainfall relations for both point and areal mean rainfall so as to meet and improve design requirements for storm and sanitary sewer systems. This is to be met using the dense raingage network data. The second objective is to develop statistics on rainfall distributions, in time and space over urban and suburban areas of varying size, for use in water quality models. This will be accomplished using the historical rainfall data in combination with the current raingage network data.

The third objective of CHAP is to develop an interface for a digital weather radar system and the MSD water resources operational system so the radar results can be used by MSD personnel. Radar operations and signal processing are being geared to develop data which will permit operators in the MSD water resource system to make better decisions, both about the likelihood of approaching rainfall as well as the rainfall quantity actually occurring over various basins of the urban hydrologic system.

The fourth objective of CHAP is to analyze the raingage and radar data so as to develop criteria for determining optimum rain measurement systems, involving either, or both, radar and raingages in other cities. Recommendations relating to operations, gage densities, digitization, level of automatic control, and other criteria will be offered in light of specific locales and climatic differences of major cities. The final objective of CHAP is the transferral of these pertinent results, both to the local and regional interests in the Chicago area, and to national interests in private practice or in governmental entities in urban water resources.

The study area for CHAP is shown in Figure 1. The sites of the 320 recording raingages are shown, along with the site of the project's radar, labeled as HOT.


KILOMETERS
0 8 16 24
RECORDING RAINGAGE & HAIL SENSOR
WEATHER RADAR
EXISTING RAINGAGE
Waukegan
Des Plaines River
Lake Michigan
Elgin
DeKalb
Chicago
Aurora
MICHIGAN
Fox River
Joliet
LaPorte
Illinois River
ILLINOIS
INDIANA
Kankakee River
Kankakee
1
2
3
4
5

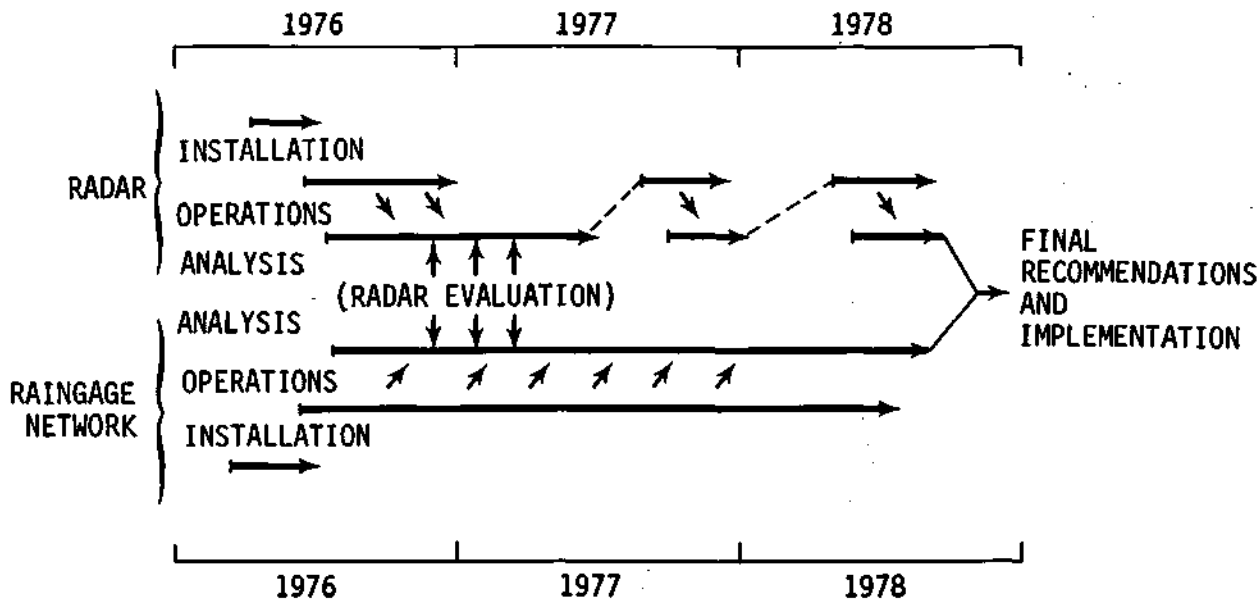
Project Framework and Components

As noted earlier, CHAP has two phases.

Phase 1. The first phase was conducted largely with state funding during the 1974-1976 period. This phase was completed in the Spring of 1976 and a major report summarizing the results has been published (Huff and Vogel, 1976). This study (Phase 1) was pursued because of a general recognition in the Water Survey of the importance of the time-space distribution of heavy storm rainfall over highly urbanized areas. It was recognized as being important to hydrologists and engineers in their design of storm sewers and other types of hydrologic structures susceptible to flooding.

All historical rainfall data from recording raingages, largely from the 1950-1970 period, were collected after conversations with engineers and hydrologists of the Chicago area. The study focused on heavy rainfall characteristics in NE Illinois including the six northeasternmost counties of the state (McHenry, Lake, Kane, DuPage, Cook, and Will). Particular emphasis was placed upon rainfall data from the Chicago inner urban area where lake and inadvertent effects modify the weather and complicate urban rainfall-runoff problems. The studies included investigations of the seasonal and diurnal distributions of storms, the synoptic weather types associated with each storm, the general shape characteristics of heavy rainfall patterns, the time between successive severe rainstorms, the storm movement distribution, the spatial distribution of heavy rainstorm centers within the region, and the relationship between the frequency distributions of point and areal mean rainfall. Several key findings resulted. For example, within the Chicago urban area a trend was found for storms to be heavier over the NW and N central parts of the city and to be less intense in the west suburbs and near the lake. Storm centers were found to occur more frequently in the urban region than in any part of the 6-county study area. Flood-producing storms, occurred most frequently in the summer season, peaking in July. These storms tended to be most intense during early to mid-afternoon. However, it was clear from the analyses of the historical data in Phase 1 that much more spatial information on rainfall was needed in and around the Chicago area to describe adequately the variations for design and storm modeling.

Phase 2. The second and more extensive part of CHAP is Phase 2, which began in late 1975. CHAP Phase 2 has three basic field facilities. A network of 320 recording raingages (weighing bucket), a sophisticated weather radar system with attached signal processor and computer, and a field facility that was designed and constructed during the first seven months of the project. Obviously, a sizeable staff representing varied scientific, engineering, and technical and analytical talents serve Phase 2. Enormous efforts involving field siting, field installation, field operations, processing of enormous volumes of data, and analysis have been the key activities. Figure 2 schematically demonstrates these activities and their interactions during the planned 3-year effort under NSF/RANN support.


1976
1977
1978
RADAR
INSTALLATION
OPERATIONS
ANALYSIS
(RADAR EVALUATION)
ANALYSIS
OPERATIONS
INSTALLATION
RAINGAGE NETWORK
FINAL RECOMMENDATIONS AND IMPLEMENTATION
1976
1977
1978

The network portion of the field program has included the network planning, the securing of sites for the 300 raingages on governmental and private property (always with an eye towards gage security and comparable exposures between raingages), and the employment and training of five field technicians to service the network raingages. These activities, conducted largely with state support, were completed in March 1976. The installation of the 300 recording raingages occurred during April-May 1976. Network operations began in June 1976, and have continued on schedule since that time.

The field program involving the HOT weather radar began with the search for a site sought south of the Chicago urban area to minimize signal blockage and attenuation problems and to allow for adequate study of approaching precipitation systems from SW, W and NW and those developing over the city. A suitable site was found on the University of Illinois Experiment Station land 15 miles south of Joliet (Fig. 1). Negotiations were begun with the University to secure use of enough land for the site. Once this had been secured, price estimates were sought through bidding procedures handled by the University of Illinois for 1) erection of a building to house the radar components, 2) to build a large reinforced cement base for the large radar antennae, and 3) for the major power installation needed for the large power requirements of the radar system. These bids and subsequent negotiations occurred during April-July 1976. The building and foundation were erected in August, as was the radar antenna base, and the power installation was largely completed by mid-August. Radar installation and erection began in September 1976, approximately 6 weeks later than originally planned. Excessive costs for power installation and the building, $16,000 above the $17,000 awarded in the NSF/RANN grant, were sought and made available through diversion of state funds. The HOT system went into operation in fall 1976, and operations have continued as scheduled.

Simultaneously, data processing and analysis efforts began at the Water Survey headquarters in Champaign-Urbana. During 1976-1977, considerable attention has been given to developing the computer software and hardware needed for optimizing application of the radar and raingage data. In a similar vein, the raingage data processing system was restructured from that of previous programs to allow for the volume of data, greater than handled previously by the data processing team at the Water Survey. For analystical purposes, digitized 5-minute rainfall data are procured, on a storm and point basis, from the raingages. The radar data, in digital form, is processed to provide digital patterns of radar-indicated rainfall at selected time intervals for various types of analyses.

The user-related interaction activities were initiated at the start of the project and have received continuous attention since that time. The extent and type of these activities are described later in this report.

Project Organization and Personnel

The organizational diagram for CHAP is presented in Figure 3. The three major functions are under the general direction of the Project Director. These include: 1) *Operations,* 2) *Analysis and Research,* and 3) *User Interactions.* Distribution of effort has involved about 45% in the Operational (installations) area, 40% in the Analysis area, and 15% in the User Interaction area.

A list of personnel presently involved in the project is presented in Table 1. Their principal title-function is shown along with each individual's time devoted to the project (at the time of this report) and the source of their salary support. Examination of support (Table 2a-2c) shows an extensive contribution of state support to this project, involving approximately 40% of the total funds expended during the first two years of NSF support and all the funds expended during the two years prior to that time.

The staff size has remained at the general level proposed to NSF/RANN for the first year efforts. An additional network technician was employed since the areal extent of the network was so great that the planned use of four technicians was found to be inadequate.

Most importantly, the project since mid-July has been functioning in an operational and analytical mode handling the output of the network and data of another Survey weather radar installed temporarily in the Chicago area (until the HOT radar becomes operational in September). All the various maintenance, operational data processing, and analyses tasks required are being conducted according to plan.

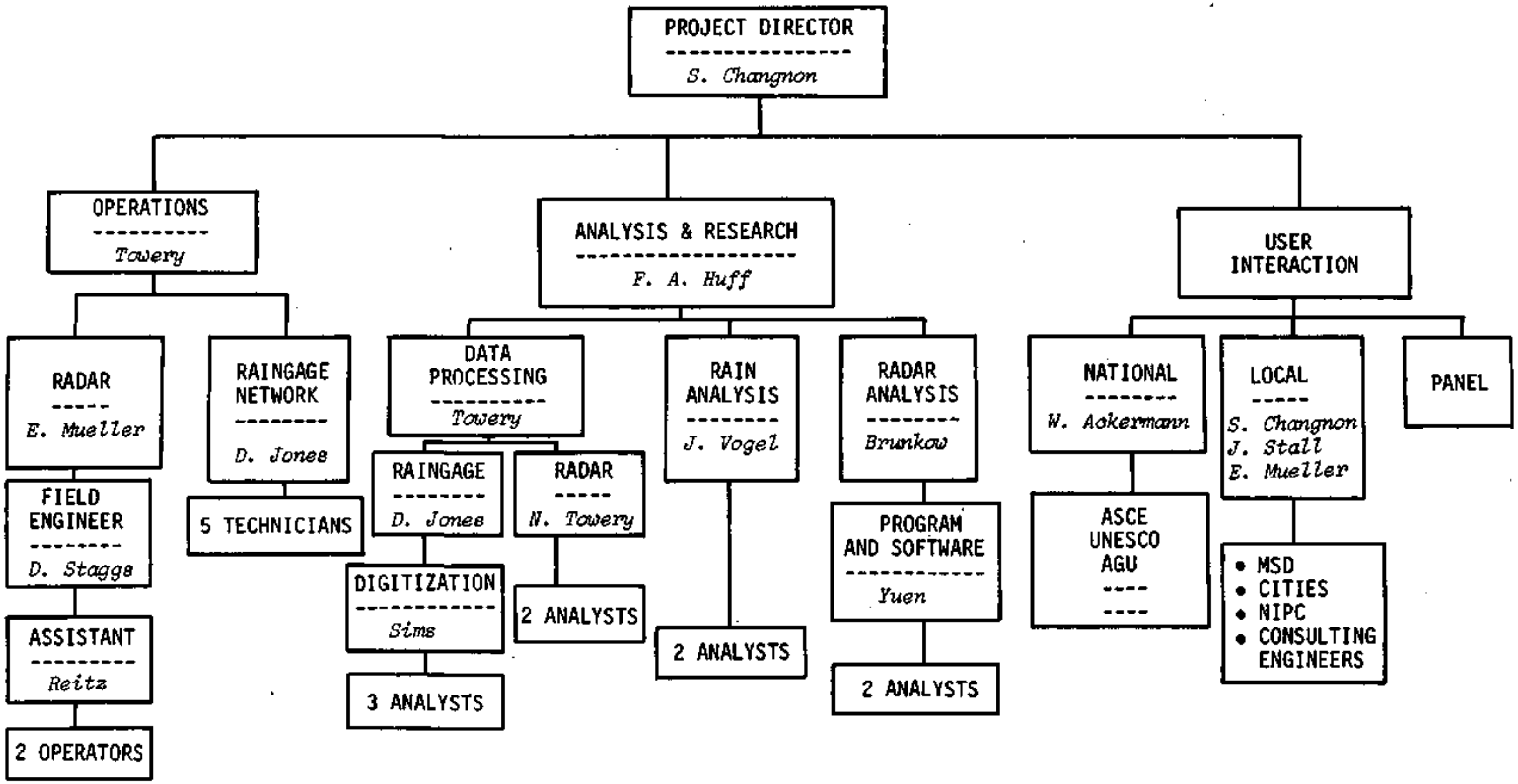

PROJECT DIRECTOR
S. Changnon
OPERATIONS
Towery
ANALYSIS & RESEARCH
F. A. Huff
USER INTERACTION
RADAR
E. Mueller
RAINGAGE NETWORK
D. Jones
DATA PROCESSING
Towery
RAIN ANALYSIS
J. Vogel
RADAR ANALYSIS
Brunkow
NATIONAL
W. Ackermann
LOCAL
S. Changnon
J. Stall
E. Mueller
PANEL
FIELD ENGINEER
D. Staggs
5 TECHNICIANS
RAINGAGE
D. Jones
RADAR
N. Towery
PROGRAM AND SOFTWARE
Yuen
ASCE
UNESCO
AGU
ASSISTANT
Reitz
DIGITIZATION
Sims
2 ANALYSTS
2 ANALYSTS
2 ANALYSTS
• MSD
• CITIES
• NIPC
• CONSULTING ENGINEERS
2 OPERATORS
3 ANALYSTS

Table 1. Support Personnel

February 1, 1977-November 30, 1977

Senior Professional Staff		Percent Time	Source of Support
S. A. Changnon	Principal Investigator	20	State
F. A. Huff	Principal Investigator	50	State
W. C. Ackermann	Engineering-Hydrologic Interactions	5	State
F. A. Mueller	Director Electronic Systems	50	Grant
J. L. Vogel	Analyst	20	State
N. G. Towery	Chief of Operations and Data	80	Grant
D. W. Staggs	Radar Engineer	100	State
D. A. Brunkow	Programmer	100	Grant
D. M. A. Jones	Network Supervisor	100	State
Junior Professional and Research Support Staff			
G. Allberg	Network Technician	100	Grant
P. Cohen	Programmer	100	Grant
M. Chung	Programmer	100	Grant
G. Fetter	Radar Operator/Analyst	100	Grant
P. Lamb	Analyst	100	Grant
J. Stewart	Network Technician	100	Grant
P. Stone	Analyst/Data Editor	80	Grant
N. Westcott	Meteorologist	100	Grant
H. Yuen	Programmer	100	Grant
P. Vinzani	Network Technician	100	Grant
G. Dzurisin	Meteorologist	100	Grant
M. Schoen	Analyst	100	Grant
K. Young	Analyst/Data Editor	100	Grant
F. Brieschke.	Network Technician	100	State
V. Selvaggio	Network Technician	50	State
I. Trover	Data Processor	80	State
E. Anderson	Analyst	100	State
R. Runge	Typist	50	State

Student Staff		Percent Time	Source of Support
R. Anderson	Programmer	50	Grant
M. Altman	Analyst	50	Grant
J. Broom	Analyst	50	Grant
C. Davis	Analyst	100	Grant
M. Aasan	Analyst	50	Grant
K. Philbin	Analyst	50	Grant
K. Powers	Analyst	50	Grant
S. Nagel	Analyst	50	Grant
L. Wu	Analyst	50	Grant
T. Welch	Analyst	50	Grant
D. Halley	Analyst	50	Grant
C. Weatherspoon	Technician	50	Grant
S. Truett	Technician	100	Grant

Table 2

Table 2a. Summary of State and NSF Support

YEAR I (February 1, 1976 - January 31, 1977)

A. NSF Support	$254,200
B. State Support	
Salaries and Wages	76,340
Fringe Benefits @ 15.2%	11,604
Indirect Cost @ 66%	50,384
Other	15,268
Total State Support	$153,596

(38% of total grant cost)

Table 2b. Summary of State and NSF Support

YEAR II (February 1, 1977 - January 31, 1978)

A. NSF Support	$236,700
B. State Support	
Salaries and Wages	78,753
Fringe Benefits @ 15.78%	12,427
Indirect Cost @ 65%	51,189
Other	15,751
Total State Support	$158,120

(40% of total grant cost)

Table 2c. Summary of State and NSF Support

February 1, 1976-January 31, 1978

A. Total NSF Support	$490,900
B. Total State Support	
Salaries	$155,093
Fringe Benefits	24,031
Indirect Costs	101,573
Other	31,019
Total State Support	311,716
C. Total Project Cost	$802,616

Scope of Report

The first part of this report provides a brief summary of the more important scientific and technical achievements to date. The second portion of the report is concerned with various activities associated with field operations. This includes the raingage network, the radar system with its associated processors and on-site computer, and development of the on-site data handling system which is critical to successful development of a real-time prediction-monitoring system.

The third portion of the report is devoted to numerous analytical tasks basic to development of the real-time system and improved design criteria for urban systems. These include such activities as: 1) processing of the raingage and radar data collected in the field, 2) radar-rainfall analyses concerned with development of a combined radar-raingage system for real-time monitoring of heavy rainstorms as they approach and cross the urban area, 3) development of echo tracking systmes pertinent to predicting the characteristics of incoming storm system, 4) hydrometeorological analyses of the network rainfall as input to the development of better methods of designing urban hydrologic structures, and 5) a description of the numerous computer programs developed to meet various analytical and operational needs. The fourth portion of the report provides a summary of user interaction during the first 22 months of the grant.

PROGRESS AND ACCOMPLISHMENTS IN FIRST TWO YEARS OF CHAP

Scientific Achievements

The first task completed under project objectives was a background climatological study of heavy rainfall occurrences in the Chicago urban area through use of historical data from an urban network of 17 recording gages in the 1949-1974 period. This study culminated in the publication of a major report (Huff and Vogel, 1976) that has been widely distributed. This investigation served as a prologue to the present large-scale field and analysis program, provided useful background information for planning this program, and provided pertinent data on the characteristics of heavy storms for utilization by urban hydrologists. The report was given wide distribution and has brought us many favorable comments from both governmental and private sources.

A second background study pertinent to the development of our real-time prediction and monitoring system was completed several months ago and a paper summarizing the results presented at the Second Conference on Hydrometeorology of the American Meteorological Society in October. This study concerned determination of radar echo characteristics associated with heavy rainfall rates in the Chicago area, and was based on data collected by the National Weather Service at their Marseilles radar located 105 km SW of Chicago. Analyses were made of the frequency distributions of echo speed, direction of movement, duration, intensity, areal extent, and vertical extent in the heavier storms experienced in 1974-1975. The results are very helpful in establishing the radar scanning, echo tracking, and prediction requirements for the real-time operational system.

As a part of Phase 2, development of improved hydrologic design criteria, analyses of outstanding heavy storms in 1976 and 1977 have been made. Two storms in the Chicago area (13 June 1976 and 20-21 July 1976) were major flash flood producers and were extreme events normally experienced at a given location on an average of once in 50-100 years. These provided much information of hydrologic significance.

In pursuing the Phase 2 studies, computer programs have been developed for reducing and filing the raingage data on disks in a form convenient for use in the hydrologic design studies and for post-analysis in the real-time research. Other programs have been developed to derive time and space distributions of rainfall in heavy storms, for making frequency analyses in these storms, and for interpolation of missing gage data which is essential to our hydrometeorological analyses. Various analyses using these programs are in progress.

In conjunction with development of the real-time prediction and monitoring system, analyses and evaluation have progressed to the point where the basic radar adjustment procedure and tracking programs for the 1978 tests and demonstration have been selected. A Water Survey modified version of the Brandes method (Brandes, 1975) has been selected as most applicable to the urban hydrology problem after consideration of various techniques presented in the literature. Various computer programs necessary to incorporate this computational method into the HOT radar system (FPS-18 and associated hardware) are nearing completion.

Echo tracking methods have been investigated and two have been selected for the rainfall prediction scheme. System movement (squall lines, cold fronts, etc.) will be tracked by a lag correlation technique. Programs have been written and the method is undergoing testing at this time. As a storm system closely approaches the urban area, a modified version of the FACE tracking program (Ostlund, 1974) will be activated to track intense convective entities within the system across the urban region. Testing and final adjustments are presently being made.

A "climatic" best-fit Z-R relation has been developed from 1976 data for use where the Brandes method is not applicable (no gage data, etc.), and, also, for determining how much improvement is achieved with the Brandes real-time adjustment procedure as opposed to an average Z-R relation applied to all storms.

A number of other computer programs needed for various computations in accomplishing Phases 1 and 2 have been written, tested, and put into use during the 22 months of this grant.

Operational-Technical Achievements

This sizeable project has had major field efforts involving the installation, operation, and maintenance of weather equipment. Also involved has been special equipment development and testing. These major achievements are listed below.

1. Siting of 320 recording raingages at locations of similar exposure and arrangements with owners of each site all completed.

2. Installation of 320 raingages in a 10,500 km^2 area completed in 4 months.

3. Continuous operation of 320 raingages from June 1976 with 15 months of data acquired. Quality control is high with only 3 to 4% data missing in any week.

4. Erection of radar facility (building constructed, cement antenna foundation poured, radome erected, trailers installed, and power lines installed) plus installation of all radar-computer equipment completed in 1976.

5. Communication system components and computer memory equipment ordered, equipment received, and interfacing with the existing radar-computer system constructed and completed in 1977.

6. Raingage data for first 15 months all edited, digitized, and processed.

7. Two periods (3- and 4 1/2-month) of radar operations completed.

8. Installation of equipment for transmission to MSD of rain estimates completed and communication system operational; radar software for use at radar site and for data display at MSD offices completed; and selected rain cases transmitted in real-time during November 1977.

FIELD OPERATIONS

Field operations continued on schedule in 1977. The dense raingage network was in full operation by 1 April and radar operations were initiated on 15 April. A brief description of these operations is provided below.

Raingage Network

The present network of 320 recording raingages in approximately 10,500 km was installed during 1976 (Fig. 1). Permission to place a raingage and hail detector on private property was started during November 1975 in Illinois and Indiana, and this task was completed by 28 February 1976.

Installation of the instruments began 8 March 1976. All available Survey instruments were installed by 1 May 1976. Instruments were not available for installation at 20 sites until 16 June. Full operation of the installed instruments began by 5 June and the completed network in Illinois and Indiana by 16 June 1976. Gaging density included 5155 km^2 at 5 km spacing and 2175 km^2 at 9.65 km spacing in Illinois; 1305 km^2 at 5 km spacing and 870 km^2 at 9.65 km spacing in Indiana. There were 301 sites being reported to the Water Survey with 298 of those belonging to the Survey, one to the National Weather Service at O'Hare Field, one to Chicago State University but operated by the Water Survey, and one to Crown Point (Indiana) Water Treatment Plant.

Interest in the project led the Geography Department of Western Michigan University to purchase and furnish 12 new raingages for the project. These were installed by the Survey staff in Berrien County, Michigan, and operation begun by 19 November 1976. An agreement was made with the University of Michigan, Ann Arbor, to receive copies of charts from four existing recording raingages in the Cook Nuclear Plant Network of Berrien County. These Berrien County sites have a 9.65 km spacing and cover a total of 1015 km^2. The total raingaged area as of 19 November 1976 was approximately 10,500 km^2.

The sites in operation had hail measurements from the time of installation in June through 31 August 1976. Twenty-one hail detectors were kept in operation in northern Indiana through 31 October 1976 for the detection of lake-effect hailstorms.

All raingaging sites were in operation until 1 January 1977 after which approximately one-half were closed for the remainder of the winter months. All operating sites used weekly recording charts. Antifreeze solutions covered with oil to inhibit evaporation were kept in all operating instruments to facilitate the measurement of snowfalls.

All sites were reactivated and in operation by 1 April 1977. As in the warm season of 1976, most sites were operated with daily recording charts, but a few weekly recorders were scattered throughout the network to ease the difficulty in determining the date of small rains on daily charts. Hail detectors were in operation by 1 June 1977 and continued in operation through 31 August although, again, 21 sites in northern Indiana were left in operation through 30 September 1977. The Illinois portion of the network was placed into wintertime operation (approximately half of the sites operating) as of 1 September. The Indiana portion of the network was placed in wintertime operation as of 1 October 1977. All Michigan sites are in operation at all times for precipitation recording.

Three raingage technicians service each raingage once a week. They are responsible for ensuring the accuracy of each clock to the nearest minute, making a stick measurement at each site for calibration purposes, and detecting any mechanical or technical problems interfering with the correct operation of each gage, such as a change in exposure due to equipment being moved too close to a site. Any difficulties encountered by the raingage technicians are reported to the field operational supervisor (Jones) at once.

Letters describing four noteworthy storms in 1976 and 1977, as recorded by the raingages, have been sent to 70 interested institutions and individuals. These letters have helped generate inquiries from consulting engineers interested in using the information from all or a particular few sites. Requests from six engineering firms have been answered, and the DesPlaines Valley Mosquito Abatement District has been supplied with copies of the gage charts for its area of interest.

Newsletters summarizing the precipitation for the summer months of 1976 and that of 1977 were sent to all of the 320 site cooperators and other interested parties. In addition, several of the site cooperators have requested the monthly precipitation totals for other months from the recorder installed on their property.

A summary of the precipitation from 1 September 1976 through 31 May 1977 shows that the southern end of Lake Michigan received the most, La Porte, Indiana, recorded the highest. Low precipitation amounts were recorded in Berrien County, Michigan, and Lake County, Illinois. A summary of the precipitation recorded by the network gages during the summers of 1976 and 1977 reveals that the most rainfall was recorded from Joliet, Illinois, to the southside of the City of Chicago. The lowest rainfall totals were recorded north of Chicago in McHenry and Lake Counties.

Radar System

As discussed in the First Interim Report under this grant, the CHILL radar was used for data collection primarily in 1976 while the HOT radar was being installed. The HOT installation required the erection of a building, concrete pads, and other facilities required for the radar system operation. All construction costs were paid for by the State of Illinois. During 1976, radar operations were initiated on 15 July and terminated at the end of September, except for some testing with the newly installed HOT system later in the fall. More details of 1976 activities are contained in the First Interm Report (Changnon and Huff, 1976).

Routine radar operations for the collection of rainfall data were initiated on 15 April 1977, and continued through 31 August. During the first part of these operations, the radar was operated when rainfall was forecast by the project duty meteorologist. After 11 June, operations were controlled by a combination of the forecasts issued by the duty meteorologist and by maintaining a 24-hr 7-day/week surveillance with the radar scanning at the maximum detectable range for precipitation detection.

There were 58 periods of operation with at least 73 independent areas of precipitation observed during 733 hours of data collection. The average duration of an operation was 12.6 hours at an average interval of 2.2 days. A summary of dates and data collected are listed in Table 3. Data were recorded on both digital tape and film during the operations. The digital tapes are the major data source used in the various analyses performed with the data. The film serves as a back-up and is useful also for some specialized types of analyses, such as checking the computer tracking of storm echoes against their actual behavior in time and space as recorded on the film. During the fall (September-November), HOT operations were carried out intermittently (Table 3). During 1977, radar and raingage data were obtained for 15 heavy storms in the network area. These were defined as those producing 25 mm of rainfall in one hour or less at one or more gages in the network. Of the 15 heavy storms, 5 were widespread in the network. This provides us with an excellent data sample for further development of real-time operational techniques.

After termination of data collection and a 6-week delay, while the commercial vendor provided telephone lines, the data link to MSD Control Center was completed in late October in preparation for demonstration of the real-time prediction-monitoring system. On days when precipitation is forecast, the equipment will be operated and a dense grid of radar-measured precipitation values are to be transmitted to the MSD Control Center.

During the data recording periods in 1977, operating personnel completed the following tasks in addition to operating the radar as needed:

1. Installed a fiberglass structure to protect the antenna reflector and drive.

2. Completed a standby radar channel.

3. Installed equipment to cool the recording chassis.

4. Installed two trailers for work areas.

5. Fabricated and installed an improved tape buffer and control for the video processor.

An additional 85 digital tapes and 3775 feet of 35-mm scope film were recorded for testing prediction techniques to be used during on-line forecasting. Transmitter calibrations were made during each operation in 1977, and 16 total system calibrations were digitally recorded to monitor system stability.

Table 3. 1977 Data Collection with HOT System

Operational Period Start	Operational Period End	Number of Precipitation Areas	Maximum Echo Intensity Light	Maximum Echo Intensity Mod	Maximum Echo Intensity Heavy	Data Film	Data Digital Tape
0800, 4/15	2300, 4/19	3	12		0	yes	yes
2300, 4/19	2400, 5/29	17	4	8	5	yes	yes
0800, 5/30	2200, 6/11	4	0	3	1	yes	yes
0800, 6/12	2150, 7/8	11	5	2	4	yes	yes
1500, 7/9	1400, 7/14	Unknown				no	no
(Shut down because of equipment problem)							
1445, 7/15	1500, 8/31	38	6	13	19	yes	yes
		Intermittent Operations					
		Hours of Operation					
9/17	9/12	16				yes	yes
10/11	10/31	27				yes	yes
11/1	11/5	24					

DEVELOPMENT OF ON-SITE DATA HANDLING SYSTEM

This section summarizes the first two years of the development of a system to make rainfall forecasts based on radar data. This system is located at the Joliet radar site, and will provide forecasts based on radar information concurrent with the forecast. Prior to the CHAP project, a Texas Instruments 980A computer with 12,288 words of memory had been interfaced to the radar antenna and was used to drive the antenna through its scan sequence. This computer system included two tape drives and a Cathode ray tube terminal as well as an ASR33 teletype terminal. The radar had been equipped with a digital video processor that was built in-house. This provided the function of digitizing the radar echoes in 1024 range bins, short term averaging of this signal, and threshold type data compression prior to archiving the data on magnetic tape.

During the first year of CHAP, the primary activities relating to the on-site data system involved the purchase of additional hardware. The TI-980 computer memory was expanded to 28,672 words. A one million word disk memory and controller was added. A Direct Memory Access (DMAC) expansion chassis was added. A surplus high-speed line printer was acquired and interfaced to the system. Two modems and a Digital Equipment Corporation LA36 hard copy terminal were purchased for use in displaying our results at a remote location (MSD).

During the second year of the CHAP project, 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 DMAC chassis. 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 provides 1024 8-bit bytes at the rate of 750,000 bytes per second. This interface provides the option of averaging 2, 4, or 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 applications programs just as the tape drives or any other input/output device is accessed.

Since the TI-980's function was to be changed from antenna controller to data handler, it was necessary to provide another device to handle the arithmetic and logical operations involved in controlling the antenna. A new micro-computer was added to the existing hardware which interfaced the TI-980 with the antenna functions. This micro-computer took over the burden of controlling the antenna while still allowing the TI-980 to access significant variables such as current antenna position, scan program status, and time of day.

During preparations for the 1977 data collection season, it was discovered that the part of the video processor which does the compression and archiving of data on magnetic tape was not working. Since the documentation and construction of this part of the processor were below standard, it was decided to rebuild these functions taking advantage of more reliable memory chips and wire-wrap connections. In the process of re-designing the data compressor, variable tag locators were added to the data fields. These tag locators function as a table of contents or index which is used to speed up processing when the tapes are analyzed. This new data compressor and tape controller have greatly improved the reliability of the archived tapes. The design and construction could not be completed before the start of the 1977 operational season. As a temporary measure, a TI-980 program was written to utilize the new radar video interface and write archive tapes. This means of recording data was used for the first half of the 1977 season. Another program was written to print out radar calibration results as the calibration was being run. This proved to be much faster than the previous method of running a calibration, dumping out the archive tape on the printer, and then picking the calibration points out of the dump.

A micro-computer based system was designed, constructed, and installed for use at the Metropolitan Sanitary District headquarters in downtown Chicago. Its function is to monitor the MSD telemetered raingages and river level gages. It calculates the daily total for each of the 23 raingages as well as 5-minute and hourly averages for the 15 river level gages. This micro-computer can be 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 allows the TI-980 to print out rainfall information while interrogating the micro-computer.

A TI-980 program was written to estimate the current rainfall in the Metropolitan Sanitary District based on the radar reflectivities and to transmit this result to MSD every 15 minutes. Each range bin's reflectivity was converted to rain rate by means of a Z-R relationship (generally, $Z=300\ R^{1.35}$ was used). Then the x-y coordinates of the bin are calculated, and that bin's rain rate is added into the nearest grid point. There is an array of 64 by 64 grid points spaced 3.2 km (2 statute miles) apart. At the end of a 15-minute time period, the average rate at each grid point is calculated. This is converted to an amount, and added into the daily total array which is stored on the disk memory. Both the last 15-minute map and the daily total map are transmitted to MSD. This program became operational during October 1977, and was demonstrated during rainstorms in early November.

RAINGAGE PROCESSING PROCEDURES

The raingage charts are forwarded each week to the Survey headquarters in Champaign, and initially undergo a manual editing process to identify usable traces and to detect possible gage malfunctions. For all traces which indicate precipitation the exact beginning and ending times, date, and revolution are fixed. Approximate storm times are determined using the weekly gages, and all potential hail storms are determined from characteristic "hail spikes" (Changnon, 1966) on the gage traces.

The precipitation data are then digitized directly from the raingage charts using a Model 3400 x-y digitizer (Auto-trol). For each chart, the Auto-trol operator records appropriate identification information along with start and end times and locations of the raingage. In addition, critical information is entered which is essential for subsequent computerized scaling and adjustment of the x-y data points and their conversion into time and rainfall amounts. The x-y data points are determined by recording a sufficient number of x, y coordinate locations which adequately describe the raingage trace. Also, any missing trace information is recorded by the operator at this time. All of the above information is filed on magnetic tape by the Auto-trol machine, and the tape data are then processed by the IBM 360-75 computer to obtain a master card file of the raingage data. After the master card file has been obtained, a visual comparison check is made between the interpreter output and each raingage chart. At this time, all errors in digitizing are corrected on the master file.

These data are stored by the computer so that data for each raingage and date may be easily retrieved. From the master computer file, rainfall amounts or rates for any storm or partial storm period can be calculated. Small error had previously been introduced into the master file during Project METROMEX when charts were changed while rain was falling (Changnon and Huff, 1976). The computer programs for CHAP have been altered to rectify this computational problem.

Very little rainfall data has been missing during the past 16 months (approximately 3-4%). However, to complete the data set estimates must be made for the missing data. During Project METROMEX, rainfall estimates were made by fitting two planes to the nearest stations with non-missing data (Schickedanz and Busch, 1975). This method proved to be satisfactory for estimates of total storm rainfall, but was inadequate and too costly for estimates of partial rainfall amounts within a storm period. A different method to estimate missing rainfall data is being used for CHAP. For each missing raingage trace an estimate of the total storm rainfall is made. The 5-minute rainfall values for the missing gages in each storm are then obtained by averaging the percent of rainfall falling in each 5-minute period at up to four nearby non-missing gages. This method is proving to be satisfactory.

HYDROMETEOROLOGICAL ANALYSES OF NETWORK RAINFALL

Since the CHAP network is so large (over 10,000 km) no attempt is being made to objectively define rainstorms for the entire network as was done for METROMEX (Schickendanz and Busch, 1975). For total network rainfall the approximate storm times developed by the raingage editors are being employed. For more specific usages the CHAP network has been divided into Hydrometeorological Analysis Rainstorm Subsections (HARS). This division is shown in Figure 4. There are nine major subsections which are listed in Table 4 along with their associated areas and number of gages. The urban subsection has been further divided into the North, Central, and South subregions. These are the regions of fundamental importance to MSD in their analysis of needs for the urban sewer system, and these subregions correspond to the areas for real-time rainfall data will be supplied during the summer operating season of 1978. For this project, only those storms which are considered to be of significance to the urban hydrologists are being studied. The criteria for determining these storms are applied to each HARS area. These criteria are:

1) the mean rainfall in the region must be 6 mm or greater in 6 hours or less, and/or

2) 25 mm or more of rain must fall at a point in less than 6 hours.

A storm is considered to begin whenever 1 mm or more of rain fell in 15 minutes, and it is ended when there was 1 hour with 1 mm or less of rain.

For each network storm with a point rainfall amount of 25 mm or more in 6 hours or less, or if the rain at a point was in excess of 12.5 mm in 1 hour or less, the following analyses are being made:

1) Storm isohyetal patterns are determined.

2) The synoptic type of each storm is specified according to a weather typing scheme utilized by Vogel (1974) in comparable METROMEX analyses.

3) The time distribution curves for individual gages and for the HARS subregions are computed according to a procedure initiated by Huff (1967).

4) Area-depth curves to define the spatial distribution of these heavier storms are constructed by the method of Huff (1968).

5) A listing and ranking of all rainfall events for periods from 15 minutes to 24 hours which are in excess of the 2-year point recurrence events, as defined by Huff and Vogel (1976) in an earlier CHAP report, are made.

6) The model storm motion is defined from raincell analysis (Schickedanz, 1974) of 5-minute rainfall amounts over the CHAP network.

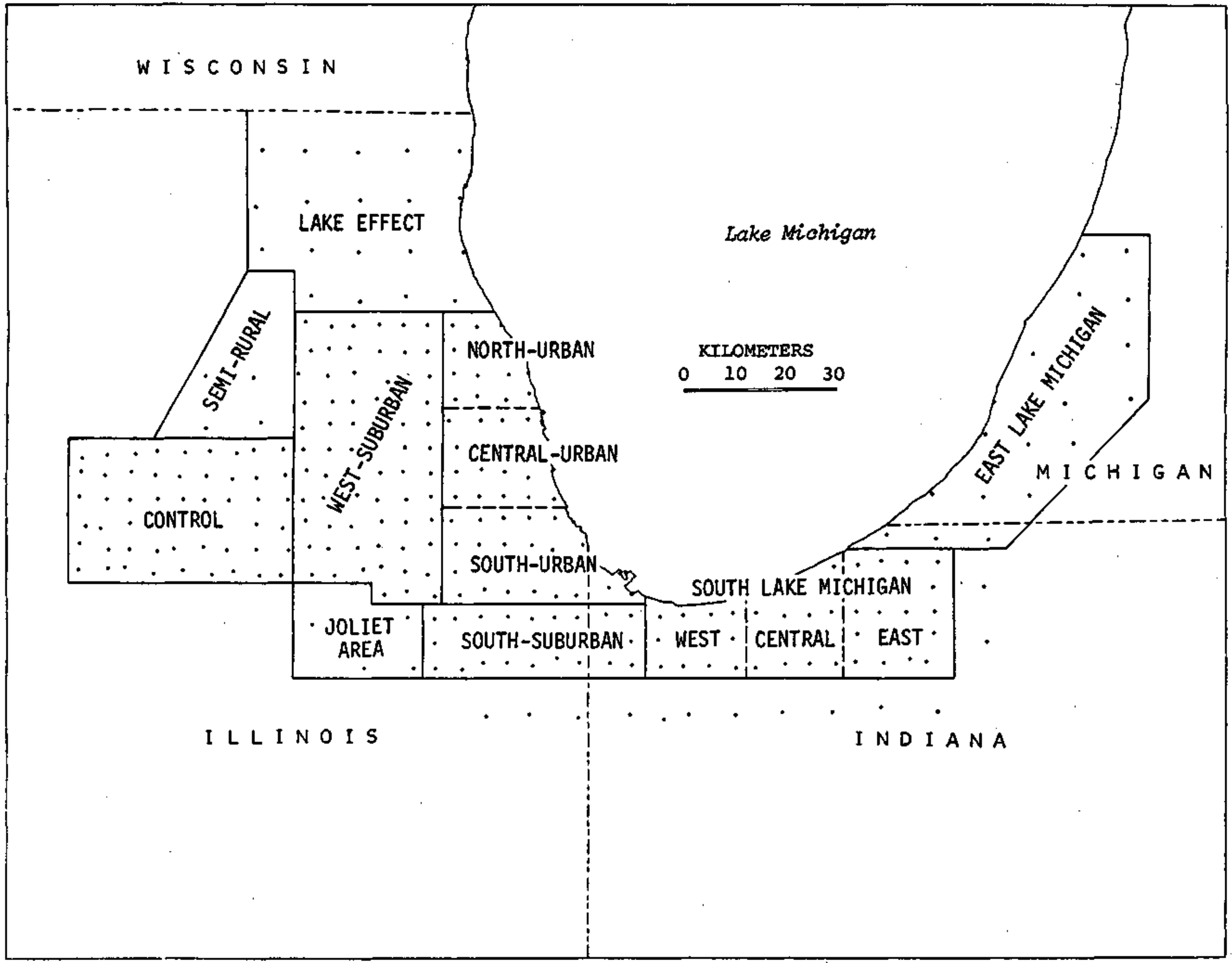

WISCONSIN
LAKE EFFECT
Lake Michigan
SEMI-RURAL
NORTH-URBAN
KILOMETERS
0 10 20 30
WEST-SUBURBAN
CENTRAL-URBAN
EAST LAKE MICHIGAN
MICHIGAN
CONTROL
SOUTH-URBAN
SOUTH LAKE MICHIGAN
JOLIET AREA
SOUTH-SUBURBAN
WEST
CENTRAL
EAST
ILLINOIS
INDIANA

Table 4. Network Subsections Used in Rainstorm Analyses--
Areas and Number of Raingages.

Subsection	Area (Km^2)	Number of Gages
Lake Effect	1710	19
Semi-Rural	635	5
Control	1280	54
West Suburbs	1655	69
Urban		
North	290	14
Central	415	18
South	605	25
Joliet	425	5
South Suburbs	590	27
South Lake Michigan	1185	48
East Lake Michigan	1625	20
Network Fringe (S-SE)	--	13

7) Storm shapes and orientation of the selected storm periods are determined using shape groupings from earlier Survey studies (Huff, 1967).

8) The listing of central point and areal mean rainfall for designated areal sizes are being tablulated to establish point-areal rainfall frequency relations for the area encompassed by the CHAP network.

Rainfall data from the METROMEX network is being incorporated into the area-depth and time distribution studies of CHAP because an initial analysis by Huff and Vogel (1977) indicates that there are no significant differences in the time and spatial distribution characteristics of rainstorms in the St. Louis and Chicago urban regions.

As part of our urban hydrometeorological studies, analyses are being made of the distribution of rainfall preceding (antecedent rainfall) heavy storms. This factor is of considerable importance in optimizing the design and operational features of urban hydrological systems. Some earlier work was done in this direction at the Water Survey through use of data from dense rural networks, and these findings will be incorporated with the results of the CHAP study.

Another study is concerned with the frequency of dry periods which is becoming of increasing importance in urban and rural areas because of surface pollution problems that tend to intensify during no-rain periods. Historical data from the Chicago area gages are being used in this study in order to obtain long records to establish frequency relations. Fortunately, areal mean rainfall is not a necessary input to this study.

Detailed analyses of all aspects of the more severe flood-producing storms in the CHAP network are being carried out. Results from three such analyses were presented by Huff and Towery (1977) at an international meeting on hydrometeorology. These case studies provide valuable information as input to urban hydrologic models. We have had frequent requests in recent years for such information from various hydrologic organizations involved in the design and/or operation of urban storm-sanitary systems.

The studies listed above are underway, but none are completed, and most will not be until the end of the project, because of the need to incorporate all available network data into the final results of each investigation.

RADAR-RAINFALL ANALYSES

Background

One of the basic goals of the CHAP Project is to develop a real-time prediction and monitoring technique using a 10-cm radar and surface rainfall information. Operation of the Chicago Hydrologic System by the Metropolitan Sanitary District (MSD) requires prediction of heavy rainfalls prior to their occurrence in the area. Development of a radar-rainfall relationship is basic to the prediction and monitoring. This has been attempted by numerous researchers with varying degrees of success. Most of the studies have centered upon developing relationships for post-hoc evaluation of entire storm periods. This is quite different from our goals of short-term prediction and monitoring.

The idea of using gage rainfall for "adjusting" the radar field is basic to obtaining a radar-rainfall relationship. Several gage-radar adjustment procedures were considered. These included those employed by Woodley, et al. (1974), Cain and Smith (1977), Brandes (1975), and other objective analyses programs. The initial decision has been to use a modified Brandes method. This decision came only after considerable analyses, which are discussed below, and consideration of various factors. These factors include the contractural goals, programming of the on-site computer (TI-980), and the density of real-time raingages which will be used to adjust the radar-indicated rainfall. Considerable time and effort has been expended in writing, modifying, and adjustment of the computer programs which are discussed in this report. The program written for the radar adjustment technique is certainly no exception.

Data Base

The processing and analyses of data collected during the 1977 operations are in progress, with only preliminary results. The results of analyses from the 1976 data are much more complete.

The bulk of data analyzed to date came from four storms which occurred from mid-July to mid-August in 1976. The surface rainfall data for these storms came from 300 recording, weighing-bucket raingages located in the area. The data from the raingages were edited, digitized, and stored on disks in a form which permits rain amounts to be determined over periods of five minutes or longer. The source of the radar data was the CHILL 10-cm power fields. The radar began operations in mid-July and continued until mid-September. The characteristics of this radar are discussed elsewhere in this report.

Data Analyses

The first processing of the radar data is performed by a program which reads the raw radar tapes and produces a cartesian grid that covers most of the raingage network. The southwest corner of the grid is located 45 km west and 61 km south of Joliet in Figure 1. The spacing between grid points is 2.4 km and the total grid coverage is 155 x 155 km. The equivalent rainfall rates (obtained from $Z = 300R^{1.35}$) from all the range bins falling within a 2.4 x 2.4 km square, centered at the grid points, are combined in an unweighted average to get the radar estimated rainfall rate at the grid point. Thus a radar grid field of rainfall exists over the raingage field. The method of combining the gage amount and radar amount begins with averaging the radar value from the four closest grid points to a gage and obtaining a radar rainfall amount at the gage. The rainfall measured by the raingage (G) is then divided by the radar amount (R) to obtain a G/R ratio. G/R correction factors are calculated for gage amounts greater than 0.25 mm per time period.

The decision to combine the gage and radar amounts in this manner came only after an exhaustive analyses to determine the best method of obtaining R at a gage location. This included examination of: 1) the distribution of the Z about selected grid points; and, 2) the distribution of G/R ratios using several methods of calculating G/R. The distribution of Z about grid points was quite noisy. The range of Z's about a grid point was from 25 to 55 dbz within one square during a 15-minute period. The distribution of G/R's was 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 means that a relatively long (30 minutes) averaging period is needed and the data has to be smoothed over a relatively large (25 km) 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 Approach

The first step in the adjustment procedure is to obtain the G/R ratio at each raingage location. In an effort to avoid spurious values often associated with light rainfalls, several thresholds have been applied. For instance, the raingage-indicated rainfall must be greater than 0.25 mm for a given time period (30 or 60 minutes) for a G/R ratio to be calculated. Also, the radar-indicated rainfall at a grid point must be greater than 0.25 mm/hour. G/R ratios greater than 10 or less than 0.10 are ignored.

Secondly, the radar-indicated rainfall value at each grid point is adjusted by multiplying it by a weighted average of all the G/R's within a specified distance of the grid point. The weighting factor used is e^{-r^2}/EP, where r is the distance from the gage to the grid point and EP is a variable weighting function. Analyses with a gage density of 1 per 25 and 50 km^2 used a weighted average of all G/R's within a 13-km radius, and an EP of 9. In analyses of gage densities of 1 per 95 and 140 km^2, a weighted average of all G/R's within a 16-km 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 raincells.

After completion of the radar field adjustment, the three sets (raingage, unadjusted radar, and adjusted radar) of rainfall data are compared. The primary parameter used for comparison is areal mean rainfall. The areal mean rainfall from the full-density raingage network is the standard by which all other rain estimates are compared. The full-density network considered in this study is divided into 5 sub-areas with sizes ranging from approximately 500 to 1600 km^2 (Fig. 1). The areal means are computed for these areas, and the percent absolute errors are also calculated by subtracting the estimated rainfall from the full-density gage rainfall and dividing by the full-density gage rainfall.

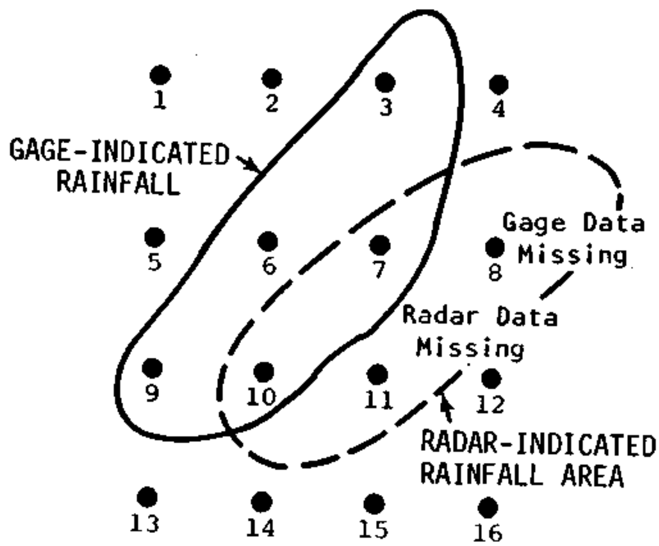
Mean areal rainfalls and the percent absolute errors from the three rainfall data sets (gages, unadjusted radar data, and adjusted radar data) have been calculated for various raingage densities (full, 1/2, 1/4 and 1/6) and for various time periods (30 and 60 minutes) of averaging the data. The purpose of reducing the gage density has been to obtain information on gage density requirements necessary for operation of a hydrologic system which would employ both radar and raingages in real time. The variation of time averaging periods has been made to determine the optimal period over which the data must be averaged to achieve acceptable accuracy.

The comparisons of areal mean rainfalls over various densities and time averaging are done using four methods of comparison. These methods of areal mean rainfall calculations are illustrated by the following example: assume the rainfall over an area, as determined by raingages and radar, is similar to that illustrated in Figure 5. The areal mean rainfall for the four methods are calculated as follows:

Method A - Non-missing - This method uses all the gages in the area except where data is missing for either the gage or radar. In Figure 5, the gage areal mean rainfall (for the specified time period) would be based on all gages in the area except #8. The areal mean radar rainfall would be based on radar-indicated rainfall at all the gages except #11. Thus, both the gage and radar rainfall amounts are summed and divided by 15.

Method B - Non-missing with rain - This method uses only the locations which have rain. The gage areal mean is based on gages 3, 6, 7, 9, and 10 in Figure 5. The gage rainfall amounts are summed and divided by 5. The radar areal mean would be obtained from gages 7, 8, and 10. The radar rainfall amounts are then summed and divided by 3.

Method C - Coincident non-missing - This method is similar to Method A. However, if either the gage or radar data is missing at a gage, the rainfall at that gage position is omitted from both calculations. The gage and radar areal mean are determined from all gages except 8 and 11. Gage rainfall amounts are summed and divided by 14. The radar rainfall amounts are also summed and divided by 14.


1
2
3
4
GAGE-INDICATED
RAINFALL
5
6
7
8
Gage Data
Missing
Radar Data
Missing
9
10
11
12
RADAR-INDICATED
RAINFALL AREA
13
14
15
16

Method D - Coincident with rain - This method uses only locations where the gages and radar indicate rainfall. The gage and radar areal means use gages 7 and 10. Both the gage and radar rainfall amounts are summed and divided by 2.

Methods A and B are the most important because they provide the values which are of most hydrologic interest, since they provide an analyses of the rainfall over a specific area. Method C is an attempt to insure that mean areal rainfall is calculated from the same gages. Method D is an attempt to alleviate the displacement of the rain measured by the two systems. All four methods are important in an evaluation of the Brandes method of adjusting the radar rainfall.

In summary, the data have been stratified several ways in the analyses. These include measurement of rainfall from three sources -- gages only, unadjusted radar, and adjusted radar. Each of these three measurements have been made for four raingage densities -- full (1 gage per 25 km^2), one-half, one-fourth, and one-sixth. There are two basic periods of averaging -- 30 minutes and 60 minutes. Each of the above stratifications have been done for four methods of comparison. (Methods A, B, C, and D.) Furthermore, the network has been divided into five sub-areas and each of the above calculations have been done for each of the areas. All of the calculations have been completed for four separate storms in 1976.

Preliminary Results

Four storms in 1976 have been extensively analyzed. The storm having the heaviest rainfall, and therefore of most hydrologic interest, occurred on July 20-21, 1976. The most important measure of rainfall in use presently is the mean rainfall over the area of rain (Method B) and in real-time operations, 30-minute averaging of the data will likely be used. Therefore, presentation of the results below will concentrate first on analyses for the July 20-21 storm with 30-minute averaging and Method B. Then the average of the four storms will be presented.

The 7-hour storm of July 20th is of immense hydrologic significance in that heavy rainfall fell over a very large area. For instance, more than 50 mm of rainfall occurred over an area of 3900 km^2. The storm is of the type that we are most concerned with in predicting and monitoring the Chicago area. Table 5 presents the results of the radar adjustment techniques for that storm. The table is based on 30-minute averaging of the radar data and is concerned only with the area of rain. The areal mean rainfall, as measured by the full density gages, had to be greater than 25 mm per time period to be included in the calculations. Presented in the table for each of the five areas and each gage density are: 1) N - the number of 30-minute samples used in the error calculation, the mean error $(\bar{X})$ obtained by gages only, the adjusted mean error $(\bar{X})$ of radar rainfall measurements, and the standard deviation (S) about the mean percent error of each procedure. The unadjusted radar erros are not shown in the table. Their magnitude was on the order of 50-55 percent for Areas 1, 2, and 3, and 40 percent for Area 4. The standard deviations were about 14 percent.

Table 5. Comparison of Absolute Percent Errors ($\bar{X}$) and Standard Deviations (8) of Gages and Adjusted Radar Data for Storm of 20 July 1976. N is the number of 30-minute averaging samples used in the calculations. The comparisons are shown for four different raingage densities. Full density, gage-only rainfall is the standard of comparison.

Gage Density	N	Gages Only $\bar{X}$	Gages Only S	Adjusted Radar $\bar{X}$	Adjusted Radar S
FULL (1 gage/25 km^2)					
Area 1	13	0	0	20	14
Area 2	13	0	0	10	9
Area 3	14	0	0	13	10
Area 4	14	0	0	32	34
Area 5		No Rain			
HALF (1 gage/50 km^2)					
Area 1	13	6	5	18	11
Area 2	13	10	7	12	10
Area 3	14	10	17	18	14
Area 4	11	14	11	31	34
QUARTER (1 gage/100 km^2)					
Area 1	13	22	14	21	9
Area 2	13	21	23	14	8
Area 3	14	21	20	17	12
Area 4	11	38	20	47	55
SIXTH (1 gage/150 km^2)					
Area 1	13	34	48	31	31
Area 2	13	28	29	23	14
Area 3	14	30	26	17	13
Area 4	11	43	36	19	12

There are several important points which should be noted. First, the adjusted radar errors are much smaller than the unadjusted radar values. Secondly, the adjusted radar values for one-fourth and one-sixth density generally are smaller than the gage-only values, indicating that the addition of the radar data is an improvement over gage-only values. Thirdly, reduction of gage density slowly increases the amount of error in all categories. Fourth, the errors in Area 4 for both procedures (adjusted radar data and gage data) are much larger, except in one case, than those for the other areas. This is likely due to the proximity of Area 4 to the radar, the loss of radar and gage data in that area, the relatively small size of the area, and the fact that the radar data was obtained from 2 antenna elevation. The data for the other areas are for the most part, obtained from the 0.5° antenna elevation.

Similar analyses to those in Table 5 were done for 60-minute averaging of the data. Some improvement was detected for all three methods of estimating rainfall. These improvements ranged from 3 to 10 percent.

Table 6 contains the results of combining all four storms and four areas (Area 4 was not used due to problems discussed above) for Methods A and B. The table presents the sample size, mean percent error, and standard deviation about the mean percent error for various gage densities, methods of areal mean rainfall calculations, and time averaging. For the 30-minute averaging, there is no appreciable difference between the mean percent error of the adjusted radar data between the two methods. This is also true for the 60-minute averaging. The adjusted radar data errors for Method B are generally less than the gage-only errors for 1/4 and 1/6 density gages. This is not always the case for Method A.

The unadjusted radar errors are approximately 65 percent for both time periods using Method A and the standard deviations are approximately 10 percent. The errors are approximately 50 percent for Method B with standard deviations near 15 percent.

Analyses identical to those in Table 6 have been done using Methods C and D. Method C produced results quite similar to Method A, and Method D produced results similar to those found with Method B. The adjusted radar errors for Method D were the least accurate of any method.

In addition to the results presented above, several target-control methods of adjustment were employed. These included obtaining an average G/R ratio at various densities from one area (control) and using that average G/R ratio to adjust the radar rainfall in other areas (targets). The adjusted radar errors were generally about 10 percent higher than those previously presented. Radar adjustment based on an average G/R obtained from gages located near the telemetered MSD gages produced similar results.

The results presented in previous tables were based upon areal mean rainfall calculations for four areas of the network. These areas were chosen because they represent areas of the approximate size encountered in urban areas. If these "artificial boundaries" are removed and radar adjustments are made with the five areas combined into one area, the percent error generally decreases 5-10 percent below those contained in Tables 5 and 6. This occurs because

Table 6. Percentage comparisons (similar to Table 1) using Methods A and B on Four Storms Combined with 30-and 60-Minute Averaging.

	30-Minute Averaging						60-Minute Averaging					
	Gage Only			Adjusted Radar			Gage Only			Adjusted Radar		
Gage Density	N	$\bar{X}$	S	N	$\bar{X}$	S	N	$\bar{X}$	S	N	$\bar{X}$	S
METHOD A												
FULL	0	0	0	19	10	9	0	0	0	20	12	14
HALF	19	4	3	19	12	10	21	7	5	20	16	13
QUARTER	19	16	18	19	19	12	21	12	10	20	14	11
SIXTH	19	15	12	19	19	14	21	22	28	21	17	15
METHOD B												
FULL	0	0	0	66	16	14	0	0	0	46	14	10
HALF	67	10	12	67	18	14	50	10	11	47	16	12
QUARTER	67	27	24	67	20	14	48	16	14	45	17	12
SIXTH	67	32	31	67	27	21	46	20	20	45	19	16

the sub-areas do not always sample the entire storm. Although this finding is not surprising nor of tremendous significance to real-time operations, it is encouraging in that it indicates the radar adjustment procedure is working well. It also has positive implications for use as a post hoc evaluation tool for other types of research, such as weather modification.

In general, the statistics in Tables 5 and 6 indicate that in the measurement of 30-minute amounts for urban hydrologic operations the radar does better than raingages alone when the gage density approaches 1 gage/150 km^2. Deterioration in the radar accuracy is relatively slow from full-density to 1/6 density, and suggests that we may be able to operate with fewer raingages than originally anticipated. Unfortunately, our preliminary results also show that the standard deviation of measurement errors is large, and this could be a problem in urban system operations that are based on the precipitation prediction-monitoring system.

Wilson (1976) in a review of the measurement of rainfall with a combination of radar and raingages found the average measurement error to vary from approximately 10 percent to 30 percent for storm periods ranging from 1 hour to 24 hours and total storm. Sampling areas ranged from 170 to 4000 km^2 and the raingage calibration densities from 1/275 to 1/3250 km^2. The preliminary results here are within the above range, but were achieved with a shorter sampling interval (30 minutes) and a greater calibration sampling density than used by previous investigators. Our sampling density was dictated by the size of individual convective entities within heavy convective storms since these must be monitored accurately for system control purposes. The utility of radar in the prediction and monitoring of heavy storms for guiding the operation of urban hydrologic systems will be clarified better when the larger sample of 1977 data are incorporated into the analyses. However, it is encouraging that we apparently are able to achieve the same level of measurement accuracy of 30-minute amounts as others have for total storm or daily rainfall.

It is likely that the full-density adjustments approach the optimum agreement that can be achieved between raingages and radar portrayal of storms. Both may be quite correctly measuring what they are sampling - the raingages the rainfall that has reached the ground, and the radar the rainfall contained in its low-level sampling volume. However, flash flooding is caused by what reaches the ground, so the radar measurement accuracy (for hydrologic uses) is limited not to how well it measures what it sees, but how well this can be interpreted in terms of surface rainfall in a specific area during a specific time period.

Initial Field Demonstrations

During early November 1977, initial tests of our real-time monitoring system were carried out in preparation for the extensive tests to be conducted during summer 1978. By November, the physical hook-up of the radar system and MSD facilities was completed. Results of these intital tests were very promising and lead us to approach the summer 1978 operations with strong feelings that the radar-raingage combination will work effectively in the urban area.

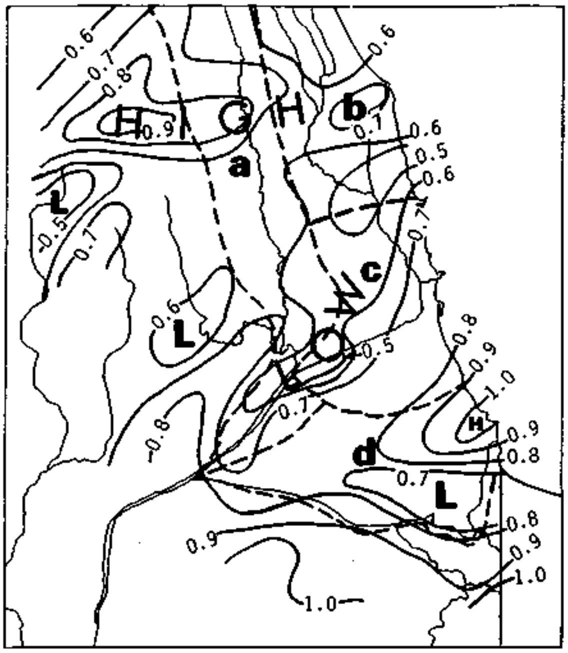
Results of the test on November 1, 1977, are illustrated in Figure 6. Figure 6a shows the rainfall pattern as determined from our dense raingage network. As indicated, 82 of the gages (winter network) were located in the main area of heavy rainfall. Figure 6b shows the rainfall pattern obtained from radar measurements with the FPS-18 on that day. Figure 6c shows the rainfall pattern obtained from 16 MSD telemetered gages in the storm region. The letters a, b, c, and d in the background indicate areas that were compared separately, and can be ignored here in evaluating the similarity of the three patterns.

Comparing the dense raingage and radar maps, a high rainfall area of approximately equal magnitude is indicated across the northern part of the urban area in both presentations. Similarly, most areas of relatively high (H) and low (L) rainfall correspond closely. The MSD gages (much fewer) indicate a good relationship with the dense raingage and radar maps in the SE part of the urban area, but not in the northern part. The close resemblance of Figures 6a and b is most encouraging, particularly since the radar pattern was obtained with no G/R adjustment. It was based on a climatic Z-R relation developed from the 1976 radar-rainfall data.

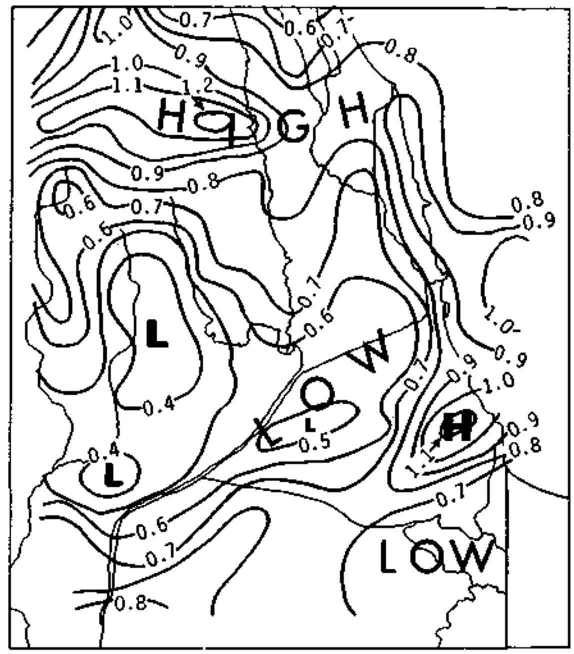
Summary of Present Status

An extensive investigation of objective techniques for utilizing a combination of radar and raingage precipitation measurements in the real-time monitoring of heavy rainstorms for urban hydrologic applications has been carried out. As the result, a Water Survey modified version of the Brandes method (Brandes, 1975) has been selected as most applicable at this time to the urban hydrology problem after consideration of various techniques presented in the literature. Various computer programs necessary to incorporate this computational method into the HOT radar system (FPS-18 and associated hardware) are essentially completed and ready to be integrated into the 1978 operational system by our engineering staff. However, the programs (software) have been prepared in a manner to facilitate rapid adjustment if continued analysis should indicate such a need.

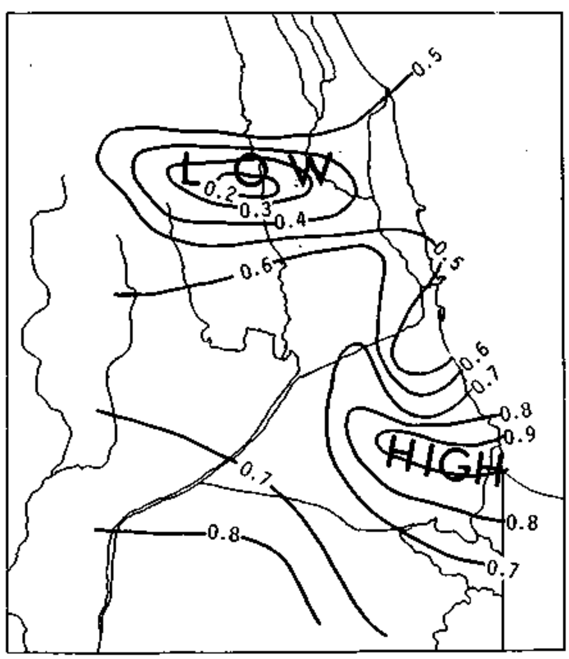
Detailed analyses of the 1977 HOT data are in progress. There were 15 days with heavy rainfall on the network (gage amounts > 25 mm) when radar data were collected. As indicated above, results of these analyses will be used to adjust the real-time monitoring system, if deemed desirable. Area-depth relationships in the subareas are being determined for both the radar and raingage rainfall fields in order to evaluate further the capabilities of the radar-raingage combination in optimizing urban hydrologic operations. The area-depth relations provide a means for evaluating the spatial distribution characteristics of the precipitation field by providing a measure of the maximum rainfall, mean rainfall, and rainfall gradient in the area of interest (Huff, 1968).



a. Pattern based on Water Survey raingages (82) developed two weeks later



b. Pattern based on radar measurements in real time



c. Pattern based on MSD raingages (16) in real time

RAINFALL PATTERNS FOR STORM ON 1 NOVEMBER 1977 (0920-1700 CDT)

RADAR ECHO CLIMATOLOGY

As part of the CHAP research, historical radar data compiled by the National Weather Service from operation of a WSR-57 (10 cm) set located approximately 105 km SW of Chicago were analyzed to determine the radar echo characteristics associated with heavy rainfall events. The radar echo characteristics of primary interest relate to echo size, intensity, movement, and duration. The climatology of heavy, rain-producing echoes provides useful input in development of the real-time, prediction-monitoring technique for the Chicago region.

Data for 1975-1976 were used in the study. Analyses were restricted to those storms which produced surface rainfall of 12.5 mm or more in 3 consecutive hours, or more than 25 mm in 6 consecutive hours. These storms include intensities which would be of interest and applicability in the operation of urban hydrologic systems. A paper presenting full details and results of this study (Towery and Huff, 1977) was presented at an international conference on hydrometeorology at Toronto in October 1977, and the paper published as part of the Preprint issue of that conference.

In general, results indicated that the heavy rain echoes move most frequently from the SW to WNW at 20-25 knots. Echo durations tend to be substantially longer than average in the heavy rain producers over the urban area, and the echo sizes tend to be much larger than normal. A very intense intensity core was frequently associated with the heavy urban echoes.

DEVELOPMENT OF ECHO TRACKING AND PREDICTION PROGRAMS

One goal of the 1978 CHAP field effort is to provide real-time forecasts of rain occurrence in the MSD's drainage areas. These will be based on computer extrapolation of current and recent radar information. The TI 980 mini-computer serving the HOT radar system will perform the processing.

Before programming the mini-computer, we will be assessing the value of two methods of tracking radar echoes and compiling echo histories for predictive use. The computer methods under study are called Lag-Correlation and FACE (after the Florida AREA Cumulus Experiment which provided the software). The two methods differ in their approach and in the information they provide to the operator. We expect to use some combination of the two in the field.

The Lag-Correlation method computes correlation coefficients for possible displacements of the entire matrix at some future time. Its output is one vector describing the mean movement of the entire echo assemblage. Its benefits are simplicity of programming and generality. Again it is the limitation of describing system movement while neglecting cellular motion. The FACE program is more complicated. It attempts to match current echoes with those from a previous radar scan, on a one-to-one basis or by identification of splits or mergers among echoes (Ostland, 1974). It offers the advantage of tracking each identified cell, but requires more storage.

Over 100 hours of radar data from 17 summer days in 1976 and 1977 have been selected for the evaluation. Criteria included availability of good quality 35-mm film of the PPI, digital tapes of radar scans, and the occurrence of greater than 25-mm of rainfall in the CHAP raingage network. A list of storm times is appended (Table 7). Radars were the 10-cm systems, HOT and CHILL, operated at Joliet and Governors State University, respectively (Fig. 1).

Regarding PPI film as 'truth' of echo positions, tracings from the film have been made. Individual echoes are hand tracked through their lifetimes. Those with 1 hour or greater duration are reduced to tables of centroid locations on a 3.2 x 3.2 km square grid overlaying the CHAP area and its westward environs. From the tables, position comparisons are made with the output of the programs. Then, motion vectors for full echo lifetime, and at 30-minute and 60-minute intervals are calculated, both for the film and the programs. These vectors are compared to give estimates of the errors to be expected from purely objective (program) extrapolation.

Individual motion vectors taken from the film are combined in each frame for testing the Lag-Correlation method. A similar combination is performed on the FACE individual motion vectors to see whether the FACE program may be able to provide both cellular tracking and prediction of system movement. The programs are run on instantaneous radar maps, 15 minutes apart, rather than on 15-minute average maps of rainfall rate. This corresponds better to the film data. Thresholds of intensity and minimum echo area are adjustable parameters in the programs.

In 1978, an operator will make real-time adjustments to the objective forecasts provided by these programs, in their final forms. A meteorologist's experience, combined with the speed and efficiency of the mini-computers data reduction, should provide the best possible real-time predictions.

Table 7. Storms Used for Evaluation of Echo Tracking and Prediction Schemes.

1976 Date	1976 Period	1977 Date	1977 Period
20-21 July	1550-0040	17 June	1630-2051
23 July	1823-2250	28 June	1432-1730
			1856-2100
26 July	1742-2110	08 July	1217-1833
			1845-2110
05 August	0400-0743	15 July	1538-2300
	1047-2006	17 July	0053-0121
			0142-0357
		18 July	0651-1130
		02 August	1227-1555
			1846-2203
		02-03 August	2215-0100
		03-04 August	2215-0815
		04 August	1123-1450
			1506-2010
		05 August	1010-2018
		28 August	1011-1635

SUMMARY OF COMPUTER PROGRAMS DEVELOPED FOR CHAP

A number of computer programs have had to be developed for carrying out various types of analyses and in developing the prediction-monitoring system. These fall into three basic categories: those utilized in various aspects of the radar-rainfall analyses associated with development of the radar-raingage monitoring system; programs necessary in development of echo tracking and prediction techniques; and, those required for expediting various analyses involving the raingage network data and methods of improving urban design criteria for hydrologic systems (hydromet analyses). A number of the more important programs developed under the project are listed below to illustrate the extensive programming required in conjunction with the research.

Radar-Rainfall Analysis

"DWREAD1", "HOTRD" and "HOTREAD" are three versions of a tape-reading subroutine, written in IBM-360 assembly language. The various versions are designed to handle different hardware configuration and recording format of the radar-processor interface for the CHILL and HOT radar. The tape-reading subroutine is used to supply a FORTRAN program with the raw radar data (reflectivity and house-keeping information) recorded on tape.

Program "CHID" is used to invoke the tape-reading subroutine and process raw radar data. The major purposes of this program are a) to convert radar data from reflectivity (dbZ) to rainfall rate (mm/hr), b) to average the rain rate over centain bins and sector at specified elevation angle for each 15-minute period, c) to map the radar-indicated rainfall onto a 64 x 64 cartesian grid and output to a disk file.

This program is currently being used as the first and very important step of getting radar-indicated rainfall data that can be used conveniently for analyses. Some of the essential parameters for this program are: Z-R relation for the reflectivity to rain rate conversion; calibration constants for the radar and hardware; origin and spacing of the cartesian grid; and relative position of the radar station on the grid.

Program "RMAIN" is an implementation of Brandes' technique of radar-rainfall adjustment. This program reads the radar-indicated rainfall (output from program "CHID") and carries out the adjustment procedure using gage rainfall amounts available from the CHAP network. The modules of this program can be modified very easily to adopt changes in: a) method of averaging and selecting G/R ratios for adjustment (modified Brandes' technique), b) method of averaging radar grid values to get radar-indicated rainfall amount at gage locations; c) formulation of weighting functions. Presently this program is tested with 1976 and 1977 radar and raingage data in searching for the best modifications of the adjustment technique that will give optimal results. Final version of the technique will be applied to the real-time radar operation in 1978.

Program "AMEAN" reads the data output from program "RMAIN". It calculates the areal mean rainfall of the raingages, plus the unadjusted and adjusted radar rainfall amounts for specified areas on the network at specified time intervals. Several methods are used to calculate and compare the three areal means. Results displayed by this program are used as an aid for evaluation of the radar-rainfall adjustment procedure.

"DRATIO" is a modified version of program "RMAIN". This program tabulates the distribution of G/R ratios of unadjusted radar-indicated rainfall at various rain rates. It is used to verify the best fit of the Z-R relation.

Program "FILTER" is used to detect and eliminate potential 'bad' radar data (isolated points with extreme high rain rates) which are probably noise. The program is applied to the data produced by program "CHID".

Echo-Tracking and Prediction

"PEAK" is a program modified from the FACE tracking program. Input to this program is the 64 x 64 grid unadjusted radar data. This program isolates and tracks individual echoes between successive time periods. Information about movement, position, area, intensity and volume of each echo are tabulated. The program is now being tested with 1976 and 1977 radar data for evaluation of its usefulness as used to model a monitoring scheme. In the near future, an extrapolation algorithm will be developed and added to this program to predict echo movement and rain volume.

Program "LAGCOR" also works on the 64 x 64 grid unadjusted radar data. Based on the information available from successive time intervals, the program determines the storm movement direction and speed using lag correlation. It will be modified to predict storm movement. This program will be put into operation with program "PEAK" for the real-time prediction-monitoring system in 1978.

Hydromet Analysis

Program "TOTAL" is used to create data files of storm totals from CHAP rainfall data. It is the first step of getting usable data for hydromet analysis. Input to this program are the digitized rainfall amounts of each gage and storm starting and ending times. It combines the rainfall amounts for specified storm periods and checks for possible errors that may have evolved during the entire data processing procedure.

Missing 5-minute gage rainfall data are to be filled by program "CHAPEST" using the Huff estimation scheme. The program utilizes the storm total with human estimates for missing gages to calculate, at each gage, the fraction of rainfall in each of the 5-minute intervals. A two-dimensional interpolation method is used to estimate the fraction of rainfall at the missing gages. This program is currently being used to replace missing data with estimates in the 1976 and 1977 CHAP 5-minute data files. Rainfall amounts at longer time intervals can be easily derived from these basic files.

Program "ADCHAP" is used to calculate spatial distribution (area-depth) of rainfall in designated areas of the network. The program is operational.

Program "TDIST" calculates time distribution of rainfall within subareas of the network. The program has to be modified from the one previously developed for METROMEX.

USER INTERACTIONS

Interaction with user groups, to obtain advice on operations and research, and to transmit results has been extensive. This applications-focused research project has already made sizeable contributions to the engineering user community to make them aware of the project.

First, to obtain advice, the project established an 8-person advisory panel. It consists of users from engineering offices of two cities (Chicago and San Francisco), presidents of two large consulting firms, a national leader in urban water resources, the head of the hydrology program of the National Weather Service and the chief engineers of the MSD of Greater Chicago and the Northeastern Illinois Planning Commission. We have met with this panel, had a site visit, obtained their advice, and kept them informed about the project. A second scientific advisory group was formed in 1977. It consists of three weather and radar specialists. Two are from National Weather Service, and one is from the university research community.

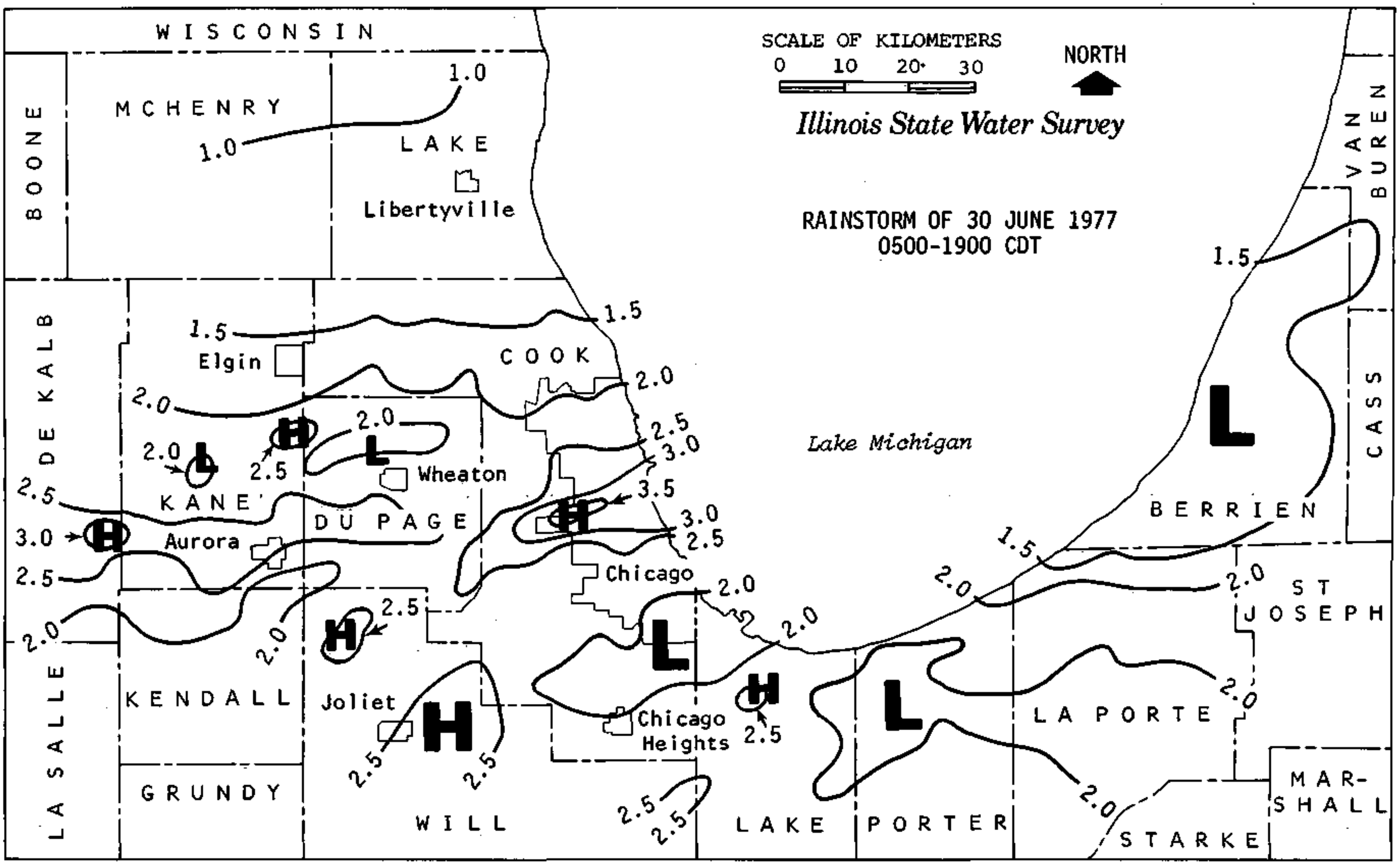
Our transfer of information, results, and data to users has been a sizeable effort, and has been pursued along several avenues. First, 11 papers have been published in hydrologic and meteorological scientific journals (see Table 8). Two user-focused reports have been generated, and as shown in Table 8, there have been three other reports published that are closely related to the project.

The considerable regional interest in project results on heavy storms has led to the preparation of isohyetal maps and information letters within two weeks after each heavy rainstorm. An example of such a pattern for one 1977 storm appears in Fig. 7. These are distributed to 75 interested users in the Chicago area. We also routinely prepare an annual rainfall summary to distribute to those 320 people with one of our raingages on their property.

Requests for rain design information and project data have correspondingly grown. In the three months ending 31 October 1977, we received and responded to 16 requests. As shown in Table 9, these were largely from engineering firms.

Since several other meteorological and hydrologic research projects have developed in the Chicago region since CHAP began, and partially as a result of CHAP, we hosted a 1-day workshop in April 1977 to develop regional communication between the 25 research scientists. We also discussed joint operations and means for data exchange between the research groups.

A major means for informing potential users about the project and to create awareness and interest in the results and techniques developed is to present scientific talks at various scientific and engineering conferences. The list of 17 talks given after 21 months of the project is presented in Table 10. These have occurred, by design, at conferences of several different user type societies (AWWA, AGU, AWRA, ASCE, and AMS), at water resource speciality conferences, and at universities. This has led to the decision at Western Michigan University to get involved in CHAP research, including the purchase of 15 raingages.


RAINSTORM OF 30 JUNE 1977
0500-1900 CDT
SCALE OF KILOMETERS
0 10 20 30
NORTH
Illinois State Water Survey
Lake Michigan
WISCONSIN
BOONE
MCHENRY
LAKE
Libertyville
DE KALB
KANE
Elgin
Aurora
COOK
DU PAGE
Wheaton
Chicago
Chicago Heights
LA SALLE
KENDALL
GRUNDY
WILL
Joliet
LAKE
PORTER
LA PORTE
STARKE
MAR-SHALL
ST JOSEPH
BERRIEN
CASS
VAN BUREN
1.0
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2.0
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H
L

The general public, particularly in Illinois, is also a user of the project information. To this end, six presentations, on either radio or TV, about the project were given (Table 11). In addition three news releases were written and published in several newspapers.

In an attempt to get direct user interaction, staff members visited with hydrologists and engineers of the city of Chicago and San Francisco, at MSD (many times), and with urban-regional planners of Chicago and St. Louis. A 1-day user workshop, and tour of the radar facility was conducted at the HOT site on 16 November. Representatives of the MSD participated in this orientation and information exchange held after the successful 1977 radar test operations.

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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.

Changnon, S. A., Jr., 1966: Note on recording hail incidences. J. Appl. Meteor., 5, 899-901.

Changnon, S. A., Jr., and F. A. Huff, 1976: Chicago hydrometeorological project: a comprehensive new study of urban hydrometeorology. First Interim Report under NSF Grant ENV76-01447, Illinois State Water Survey, Urbana, 69 pp.

Huff, F. A., 1967: Time distribution in heavy storms. Water Resources Research, 3, 1007-1019.

Huff, F. A., 1968a: Spatial distribution of heavy rainfalls in Illinois. Water Resources Research, 4, 47-54.

Huff, F. A.] 1968: Area-depth curves -- a useful tool in weather modification experiments. J. Appl. Meteor., 7, 940-943.

Huff, F. A., and N. G. Towery, 1977: Hydrometeorological characteristics of severe rainstorms in Chicago metropolitan area. Preprints, Second Conference on Hydrometeorology, Amer. Meteor. Soc, 214-219.

Huff, F. A., and J. L. Vogel, 1976: Hydrometeorology of heavy rainstorms in Chicago and Northeastern Illinois, Phase I - Historical Studies, Rept. of Inv. 82, Illinois State Water Survey, Urbana, IL, 63 pp.

Huff, F. A., and J. L. Vogel, 1977: Time and space distribution models for urban rainstorms. Paper presented at Second Conference on Hydrometeorology, Amer. Meteor. Soc, Toronto, Canada, October 25-27.

Ostlund, S. S., 1974: Computer Software for Rainfall Analysis and Echo Tracking of Digitized Radar Data. Tech. Memo, ERL WMPO-15, N0AA, Coral Gables, FL, 82 pp.

Schickedanz, P., 1974: Inadvertent rain modification as indicated by surface raincells. J. Appl. Meteor., 13, 891-900.

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Vogel, J. L., 1974: Synoptic Analyses. Interim Report of METROMEX Studies, NSF Grant GI-38317, Illinois State Water Survey, Urbana, 6-16.

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Table 8. Bibliography of Project Publications.

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

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.

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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.

Vogel, John, 1976: "Heavy Rainfall Relations in a Major Metropolitan Area." Preprints Conference on Hydrometeorology, Amer. Meteoro. Soc, Boston, 86-91.

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

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. Sewerage Agencies, Washington, DC, J3-J13.

Huff, F. A., and S. A. Changnon, Jr., 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.

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. Meteoro. Soc, Boston, 286-289.

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Table 8. (Continued)

Closely Related Reports of Other Water Survey Research and Staff

Gatz, D. F. and S. A. Changnon, Jr., 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 Effect on Storm Runoff. Illinois State Water Survey, 68 pp.

Table 9. Requests Received During August-October 1977 for CHAP-Derived Results and Data.

Requestor	Item Requested
Alvord, Burdick & Howson	Extreme urban rain data
" " "	Rain info. and design values
" " "	Rainstorm data
City of Chicago, Engineering Division	Monthly rain and extreme rain event maps
City of Chicago, Dept. of Water and Sewers	70 copies of heavy rain maps
Deuchler, W., Engineers	Urban rain data
Environmental Association, Inc.	Urban rain data
Greeley and Hansen	Severe rainstorm maps
Harza Engineering Co.	Project Plan, rain data, and add to project mailing list
Madigan, Congressman Edward	Thanks for rainstorm information
Metcalf and Eddy, Inc.	Time distributions of heavy rains
RJN Engineering Resource Consultants	Heavy rain data
Smith, G., Engineering Co., Inc.	Rain data
" " " " "	Specific rainstorm results
Western Michigan University	Rain data
Hydrocomp	Rainfall data

Table 10. Professional Papers and Technical Presentations.

"The Chicago Hydrometeorological Program," given by F. A. Huff, Annual Meeting of American Geophysical Union, Washington, DC, March 1976.

"A Hydrometeorologic Systems 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 A.M.S., 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.

"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.

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

"A Review of the Chicago Hydrometeorological 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 Areas," given by F. A. Huff, International Symposium on Urban Hydrology, Amsterdam, October 1977.

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

Table 10. (Continued)

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

"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 Hydrologic Applications," given by F. A. Huff, Conference on Water Quality Surveys for 208 Projects, April 1977.

Table 11. Presentations to Non-Technical Audiences.

"Urban Rainfall," radio interview, NBC Chicago, May 26, 1976, by S. A. Changnon.

"Water and Weather in Illinois," taped talk, WJJD Radio, Chicago, July 5, 1976, by S. A. Changnon.

"Impacts of Weather," TV taped talk, Illinois Agricultural Association, Bloomington, January 4, 1977, by S. A. Changnon.

"Weather Research in the Future," talk, Central Illinois Chapter of AMS, Champaign, January 27, 1977, by S. A. Changnon.

"Weather and You," radio talk, Waukegan station, Waukegan, Illinois, March 4, 1977, by S. A. Changnon.

"Urban Water Resources and the Rain Problem," radio talk, University of Illinois Network of 28 stations, March 1977, by S. A. Changnon.