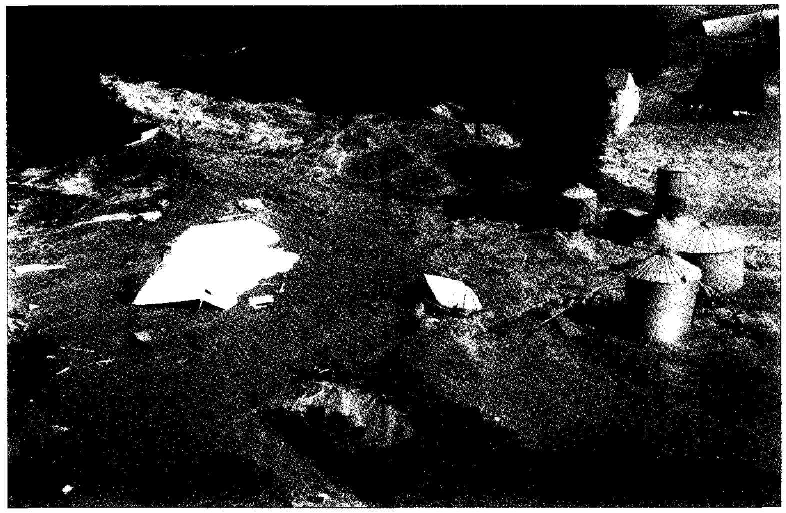
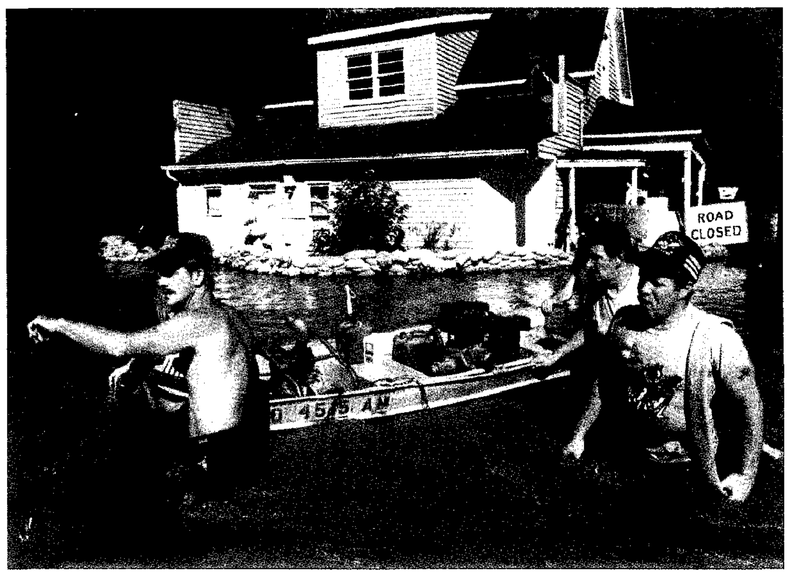
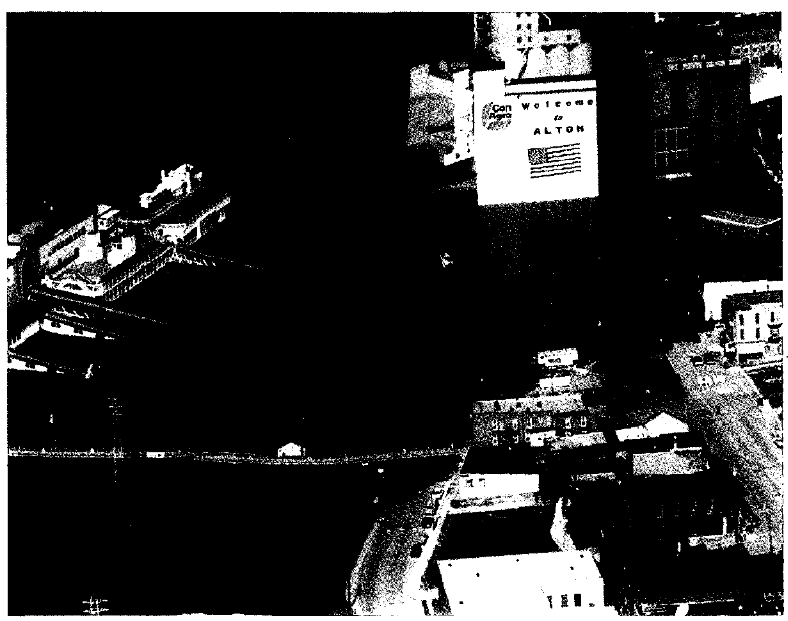
DEPARTMENT OF COMMERCE · UNITED STATES OF AMERICA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION · NOAA · U.S. DEPARTMENT OF COMMERCE

Natural Disaster Survey Report

The Great Flood of 1993







Natural Disaster Survey Report

The Great Flood of 1993

February 1994

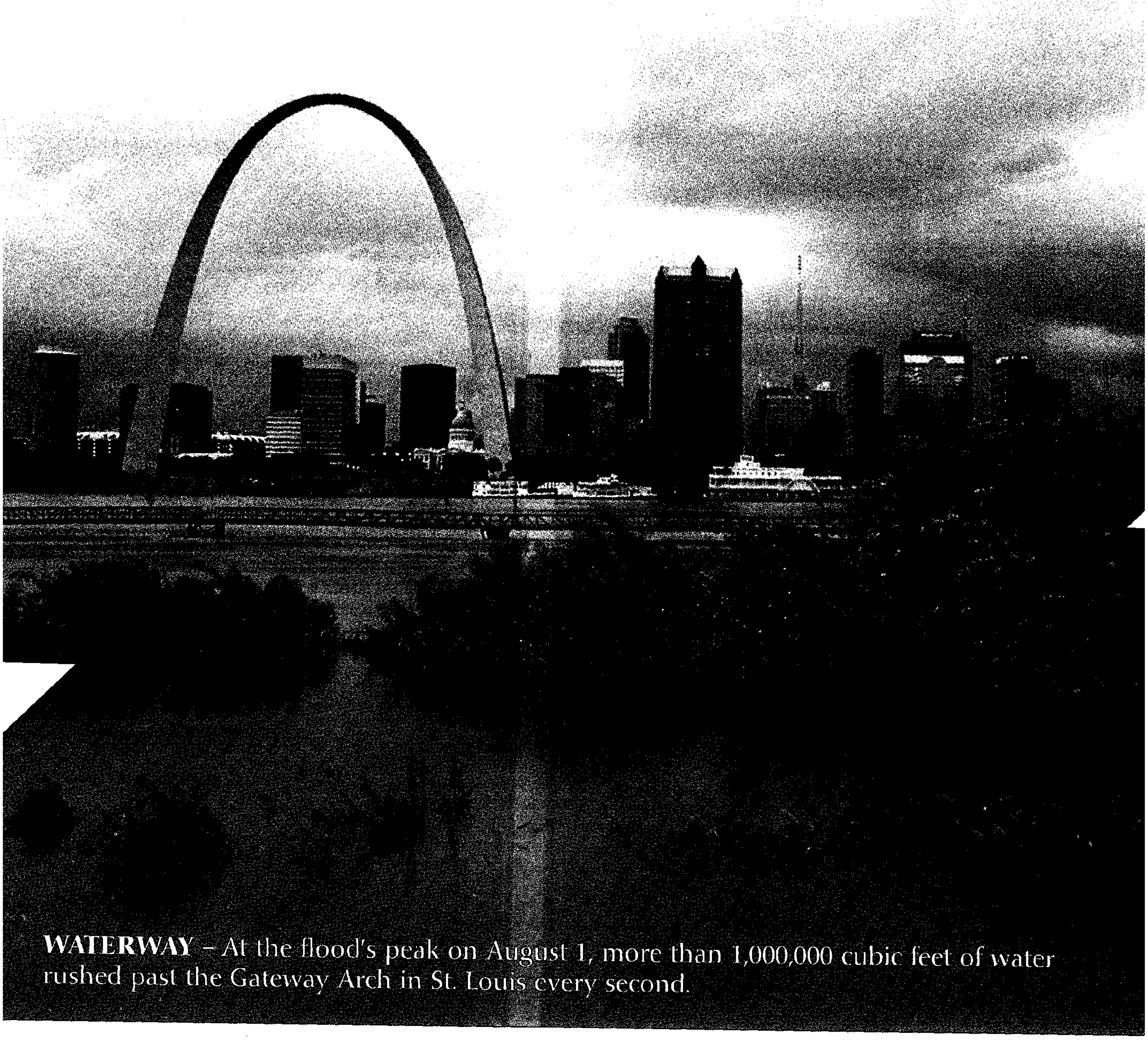
U.S. Department of Commerce
Ronald H. Brown, Secretary

National Oceanic and Atmospheric Administration
Dr. D. James Baker, Administrator

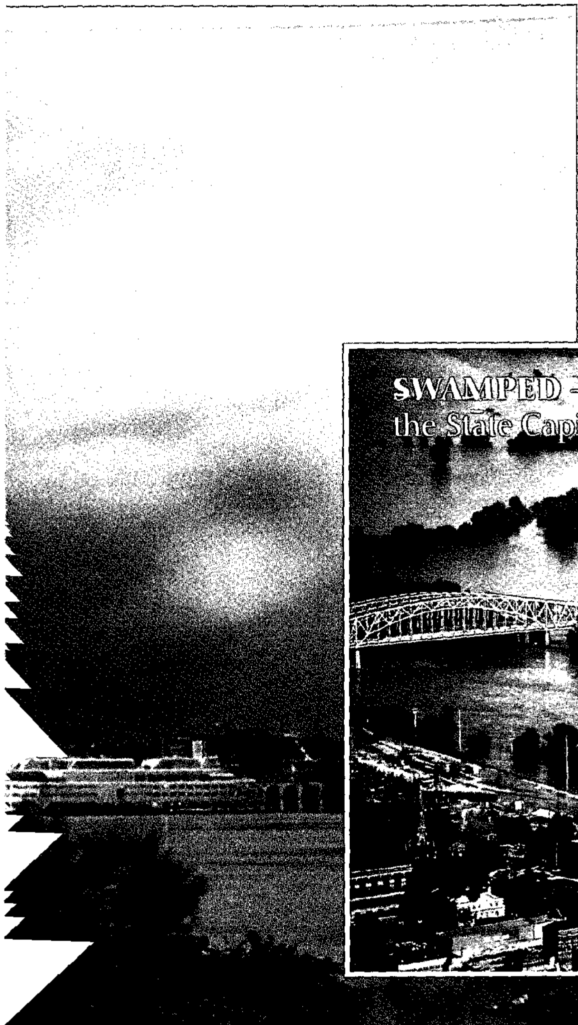
National Weather Service
Dr. Elbert W. Friday, Jr., Assistant Administrator


THE KANSAS CITY
THE FLOOD OF '93
River's crest moves east
Water claims bridge, historic homes and key highways
ALL WET!
Kansas loses battle with rising waters
The Ottumwa Courier
Ottumwa sets evacuation
Authorities prepare for the worst
Expect more
Despite the rain, taxes still due
ILLINOIS EDITION
Quad-City Times
RIVER RISES INTO HISTORY
OK
NO
PROGNOSIS
Missouri River On Rampage
Des Moines Register
Burials delayed by flooding
Cemetery crews are too busy helping sandbag
$1 million a day lost to floods
Towboat industry
Floods cripple Des Moines; entire city without water
Downtown may lack electricity for a week
Disaster center to open today
It's a record!
River hits 22.52, topping '65 level
THE DISPATCH
Days of disaster
Argus Leader
Crop loss figures soar
Volunteers fight to save W.D.M.
Cleanup creates jobs for many unemployed

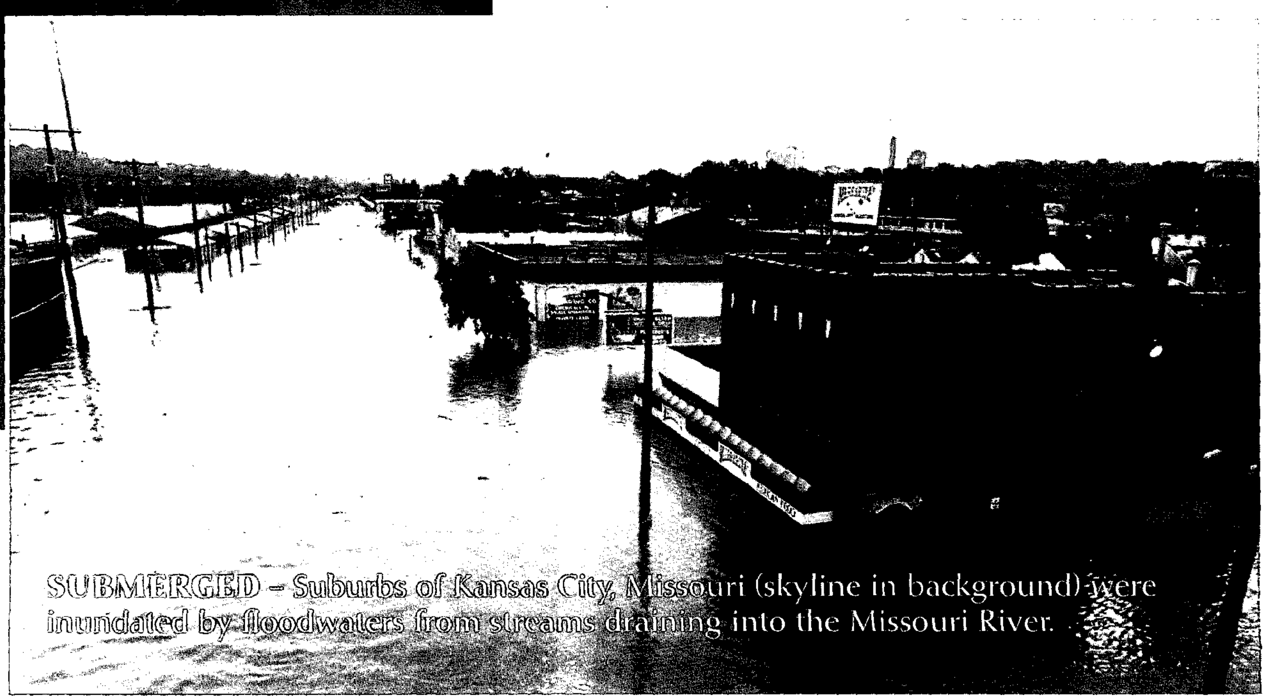
Cities



WATERWAY – At the flood's peak on August 1, more than 1,000,000 cubic feet of water rushed past the Gateway Arch in St. Louis every second.

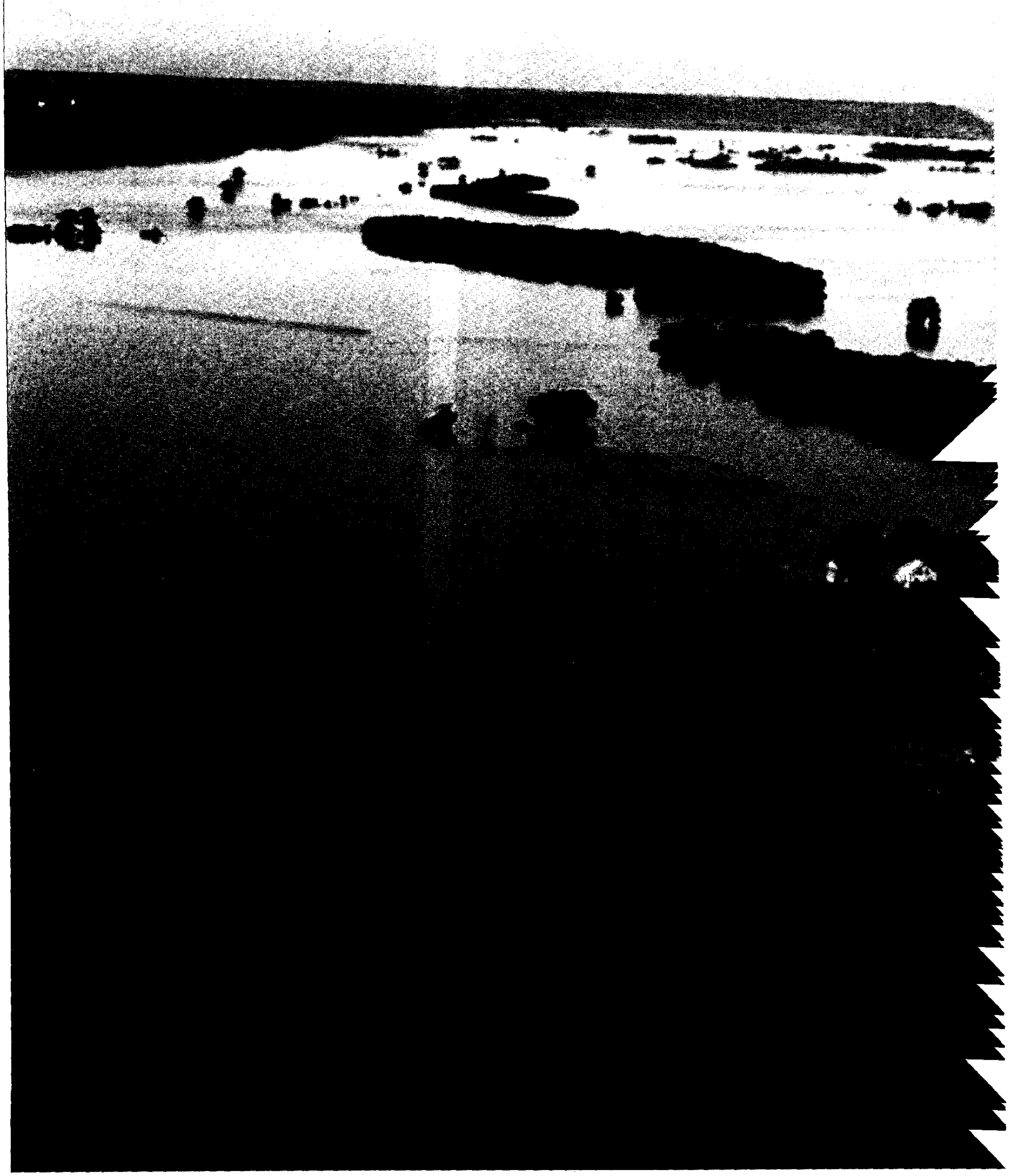


SWAMPED – Missouri River floodwaters lap at the State Capitol in Jefferson City, Missouri.

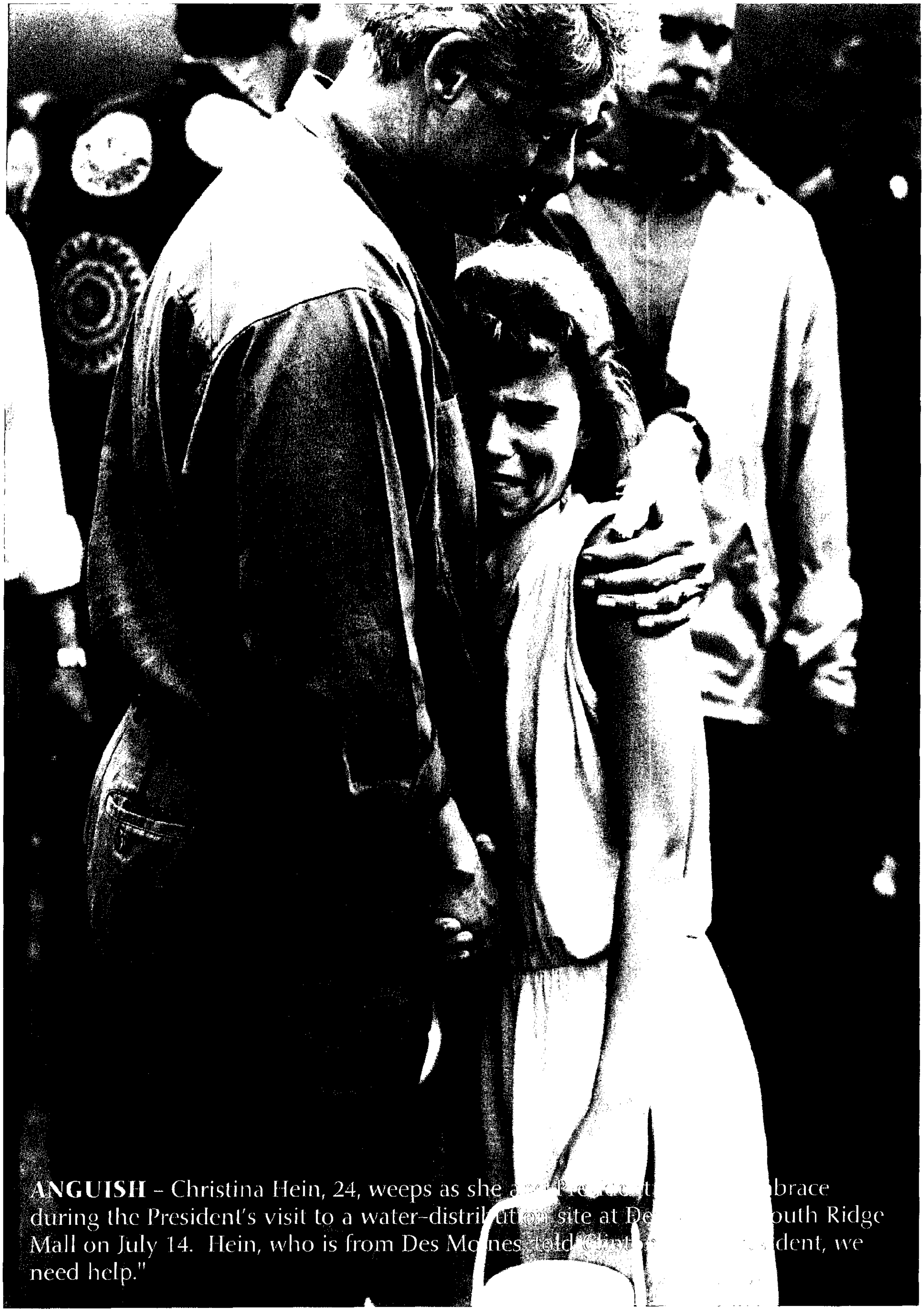


SUBMERGED – Suburbs of Kansas City, Missouri (skyline in background) were inundated by floodwaters from streams draining into the Missouri River.

Water, Water Everywhere

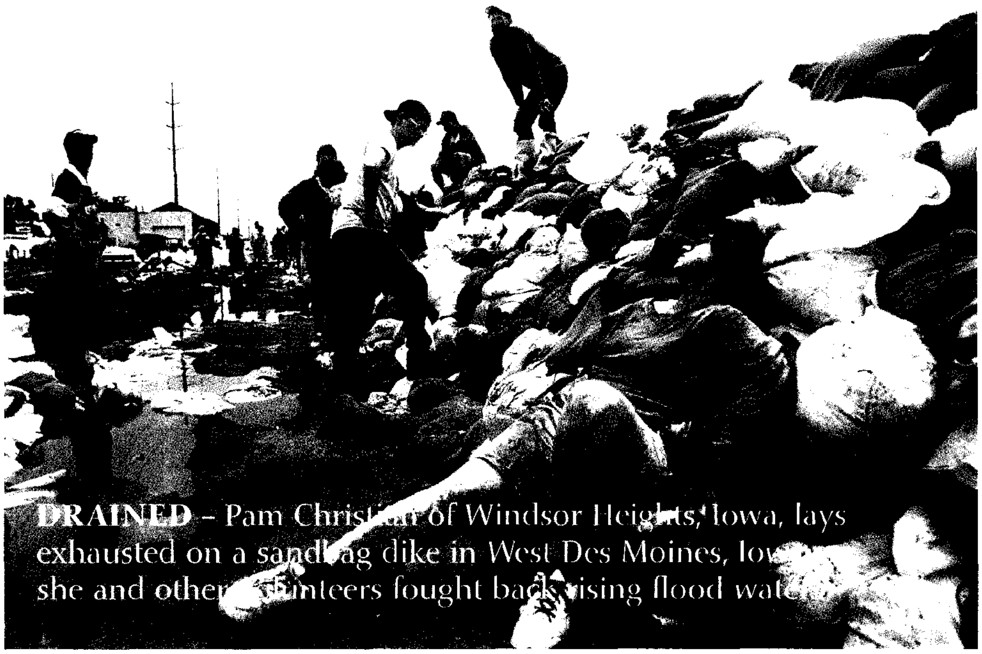


ENGULFED –The Mississippi River widens into the flood plain of Monroe County, Illinois.



ANGUISH - Christina Hein, 24, weeps as she a[illegible] Pre[illegible] [illegible]brace during the President's visit to a water-distrib[illegible]tion site at De[illegible] [illegible]outh Ridge Mall on July 14. Hein, who is from Des Mo[illegible]nes, told [illegible] [illegible]dent, we need help."

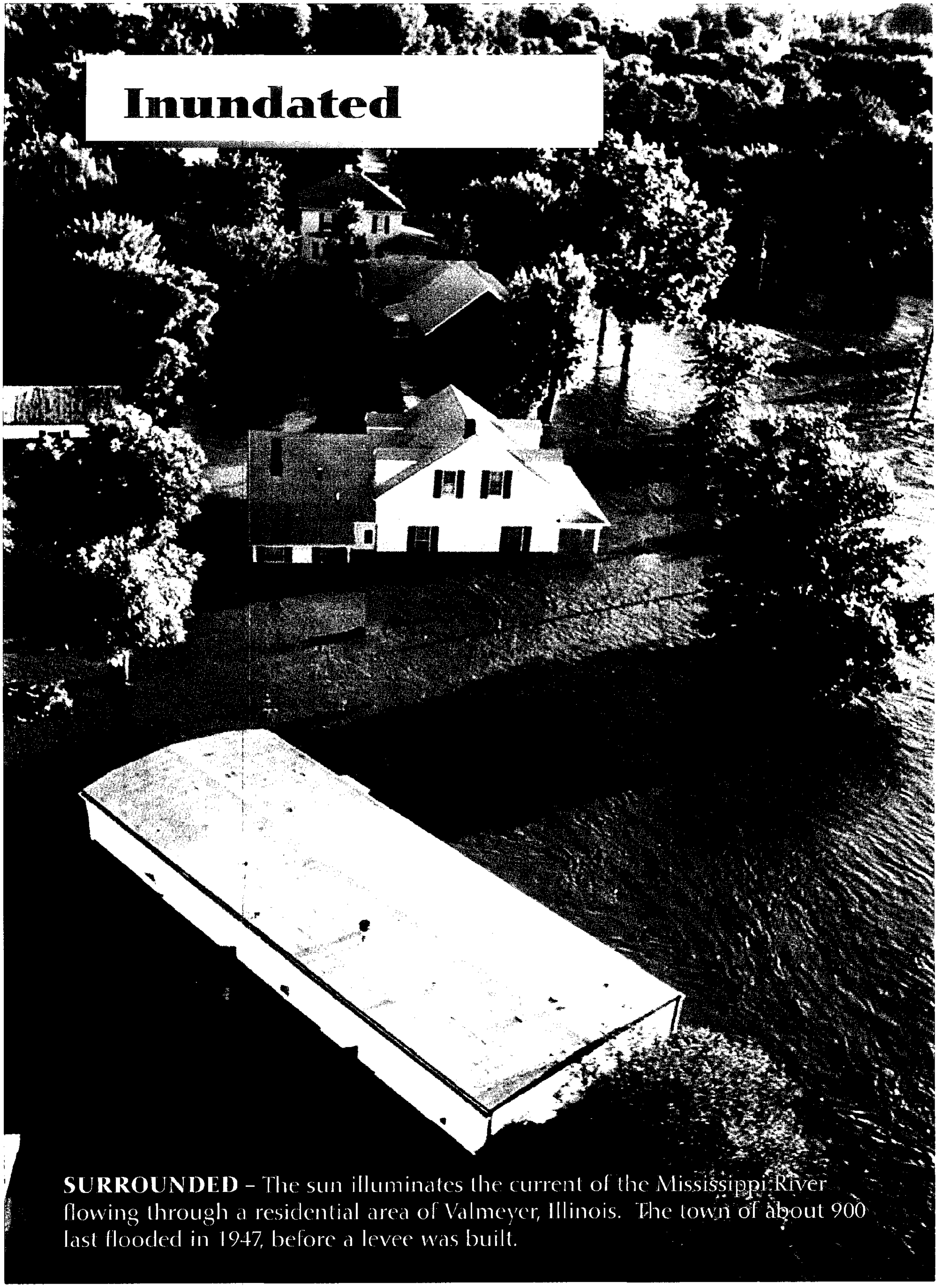
Not a Drop to Drink



DRAINED – Pam Christian of Windsor Heights, Iowa, lays exhausted on a sandbag dike in West Des Moines, Iowa, as she and other volunteers fought back rising flood waters.

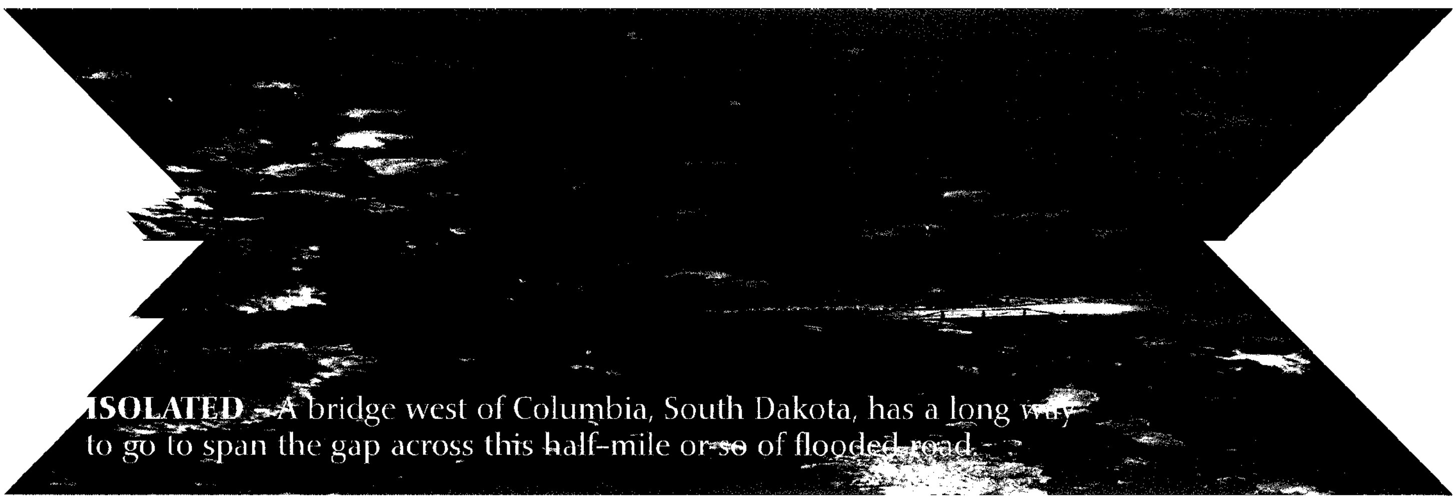
OVERWHELMED – Aerial view of water works plant at West Des Moines, Iowa, on July 17, 1993.

Inundated

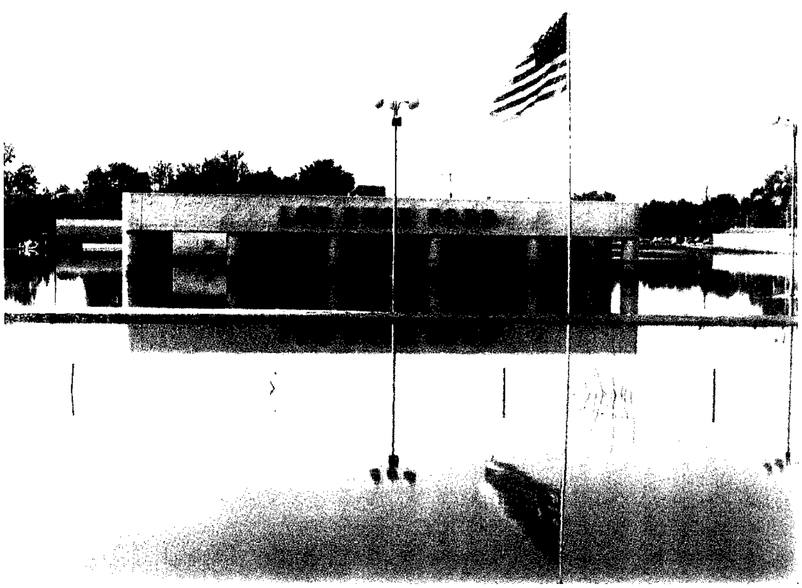


SURROUNDED – The sun illuminates the current of the Mississippi River flowing through a residential area of Valmeyer, Illinois. The town of about 900 last flooded in 1947, before a levee was built.

PROPHETIC – Floodwater from the Missouri River at St. Charles, Missouri, on July 21, 1993.

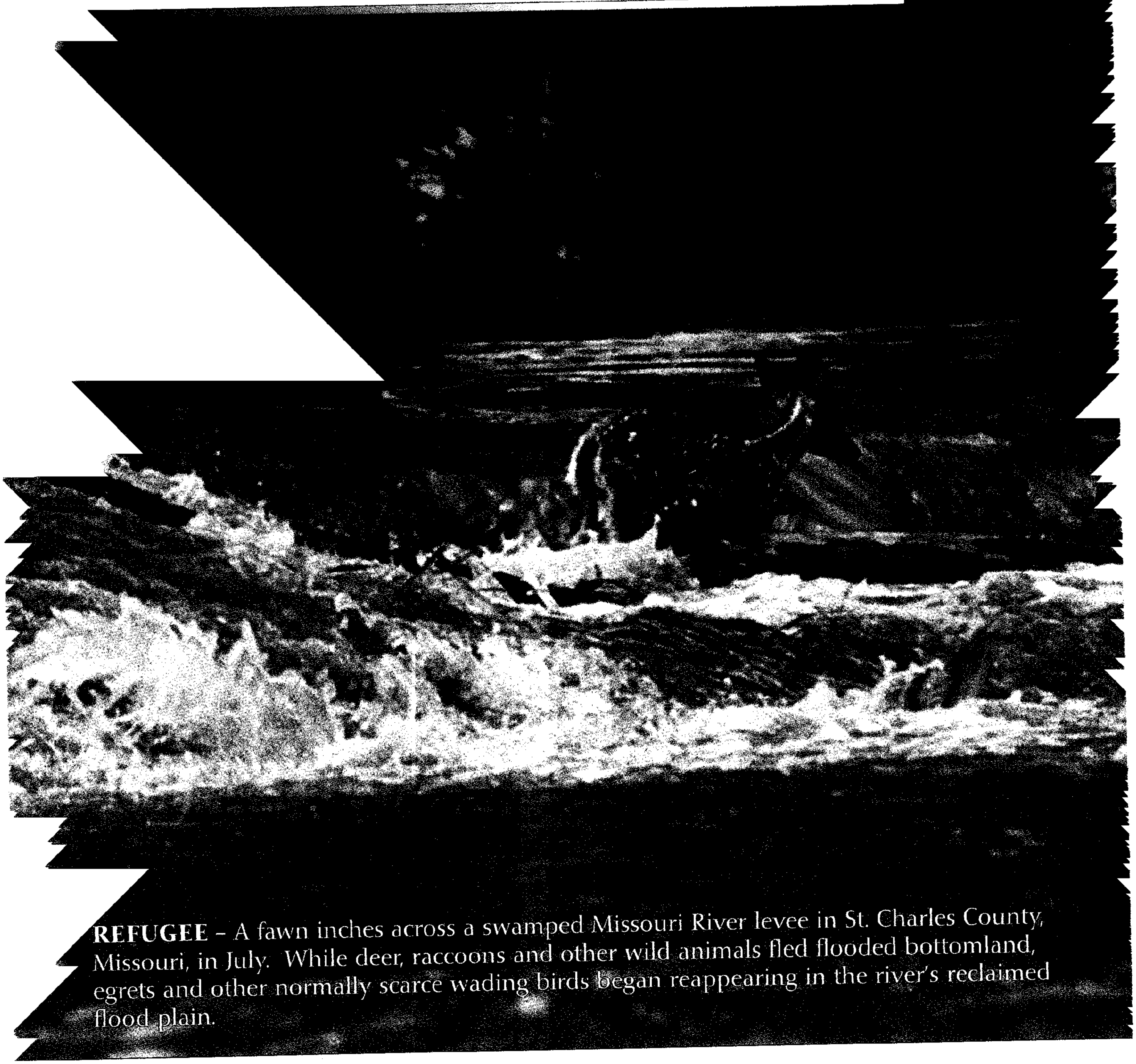


ISOLATED – A bridge west of Columbia, South Dakota, has a long way to go to span the gap across this half-mile or so of flooded road.

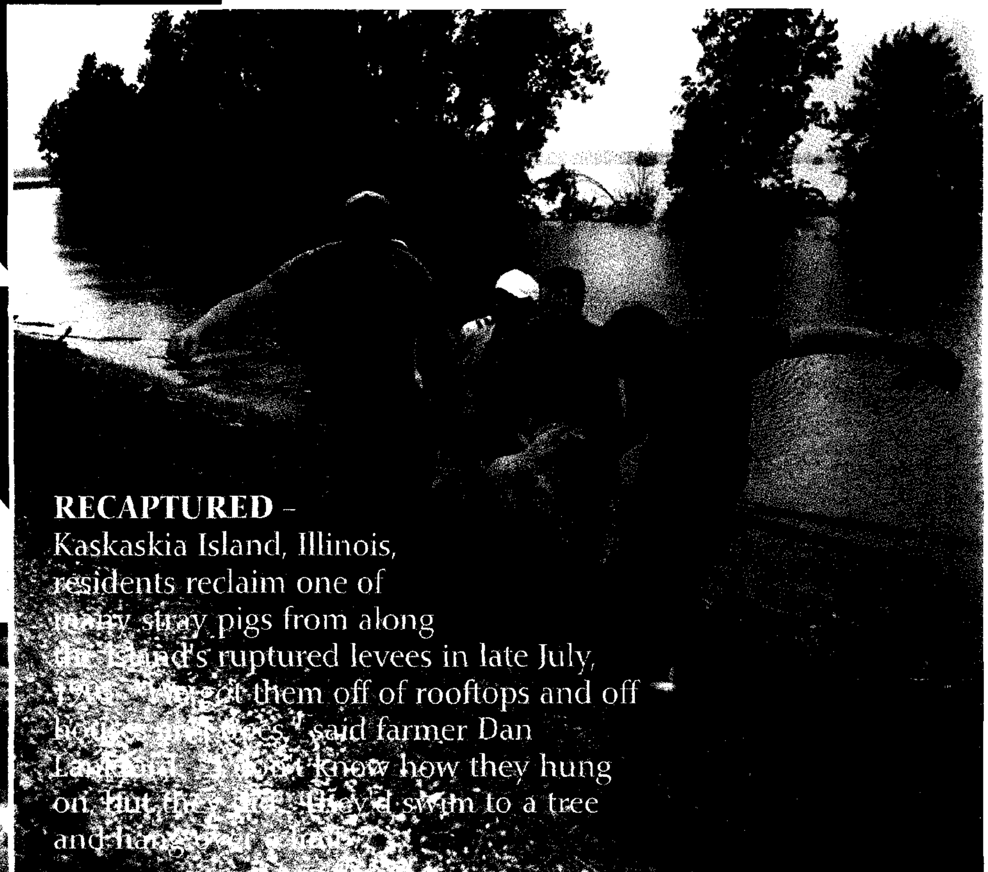


CLOSED – The Lou Fusz Ford dealership in the Chesterfield Valley of St. Charles, Missouri, was one of 500 businesses inundated when a Missouri River levee failed..

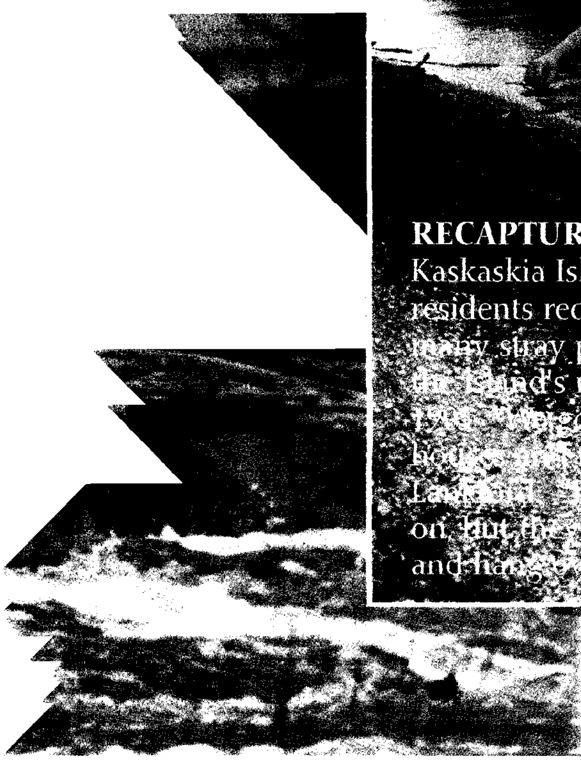
All Creatures Great & Small



REFUGEE – A fawn inches across a swamped Missouri River levee in St. Charles County, Missouri, in July. While deer, raccoons and other wild animals fled flooded bottomland, egrets and other normally scarce wading birds began reappearing in the river's reclaimed flood plain.



RECAPTURED – Kaskaskia Island, Illinois, residents reclaim one of many stray pigs from along the Island's ruptured levees in late July, 1993. "We got them off of rooftops and off houses and trees," said farmer Dan [illegible]. "I don't know how they hung on, but they did. They'd swim to a tree and hang over [illegible]."

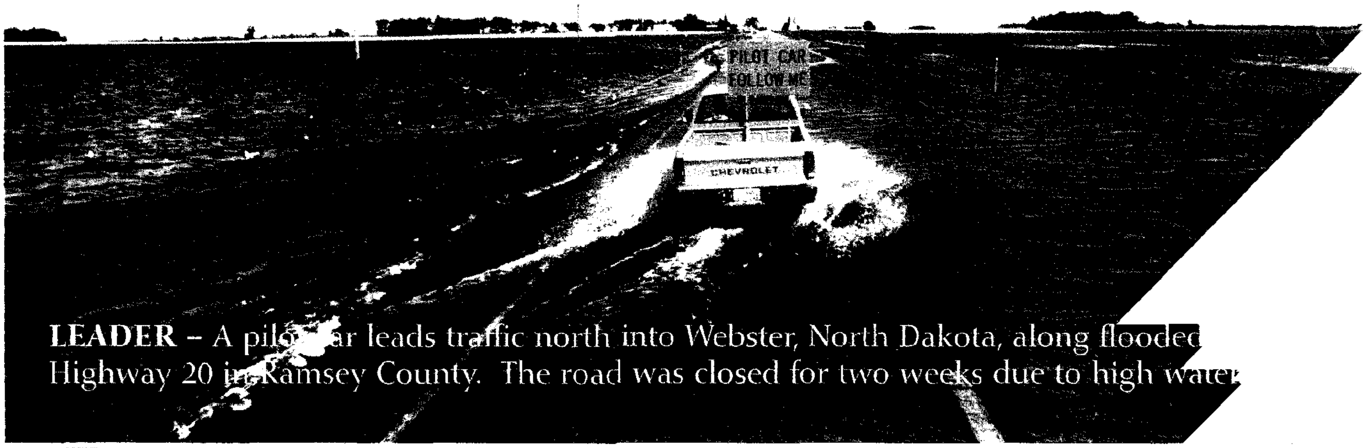


CONSTERNATION – Larry Katz braves fast moving flood waters to save his cat, Tom, in West Des Moines, Iowa. A dike holding back a nearby river failed during the night, making Katz dash hastily for higher ground. Tom was left behind in the confusion and is shown being rescued.

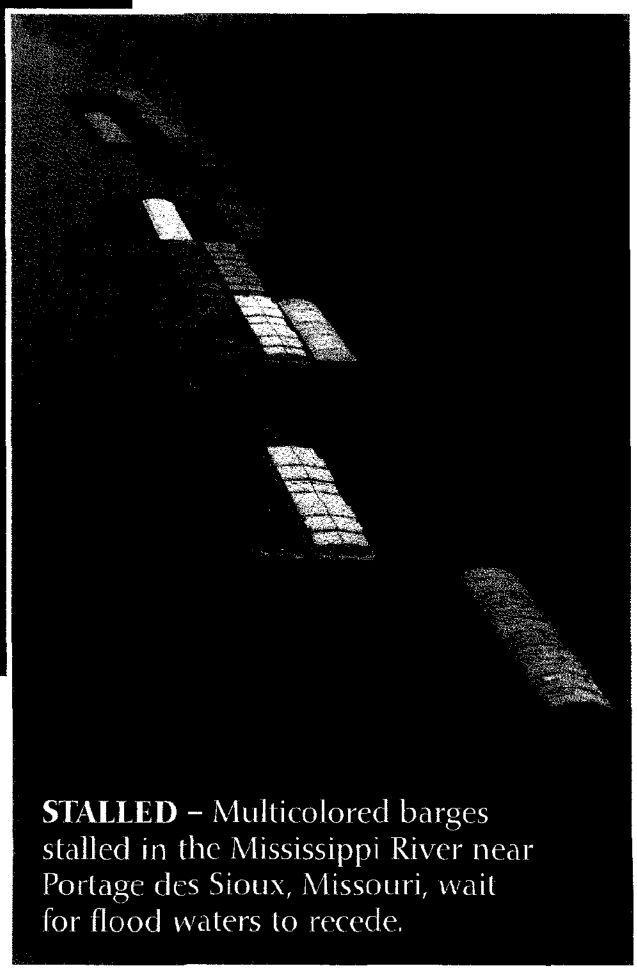
Transportation

SNAGGED - Flood waters scooped up two planes at the Spirit of St. Louis Airport in Chesterfield, Missouri.

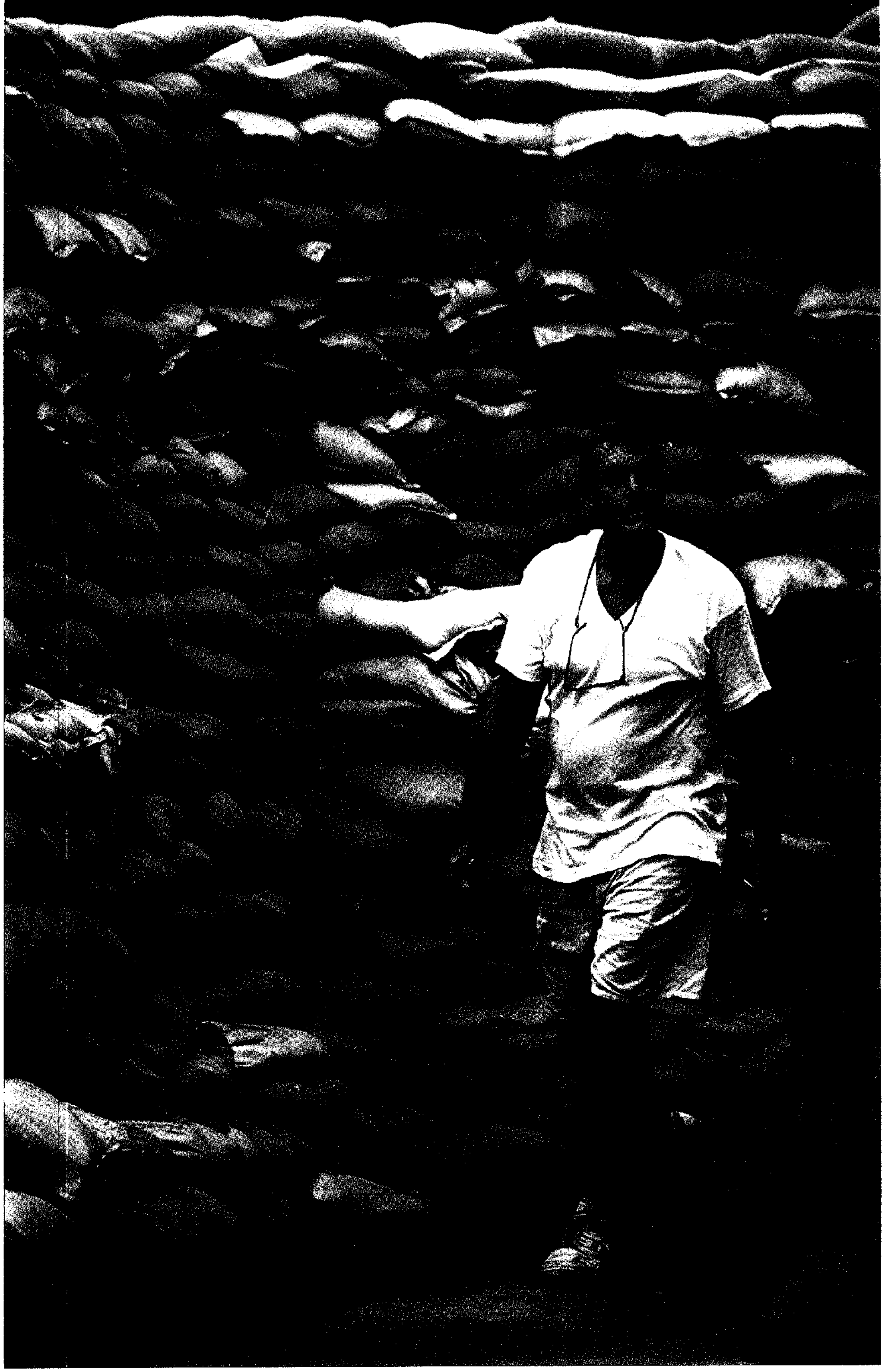
WASHOUT - A Burlington Northern Railroad manager walks on granite roadbed material washed out from under rails by flood waters near Rock Port, Missouri.



LEADER – A pilot car leads traffic north into Webster, North Dakota, along flooded Highway 20 in Ramsey County. The road was closed for two weeks due to high water.



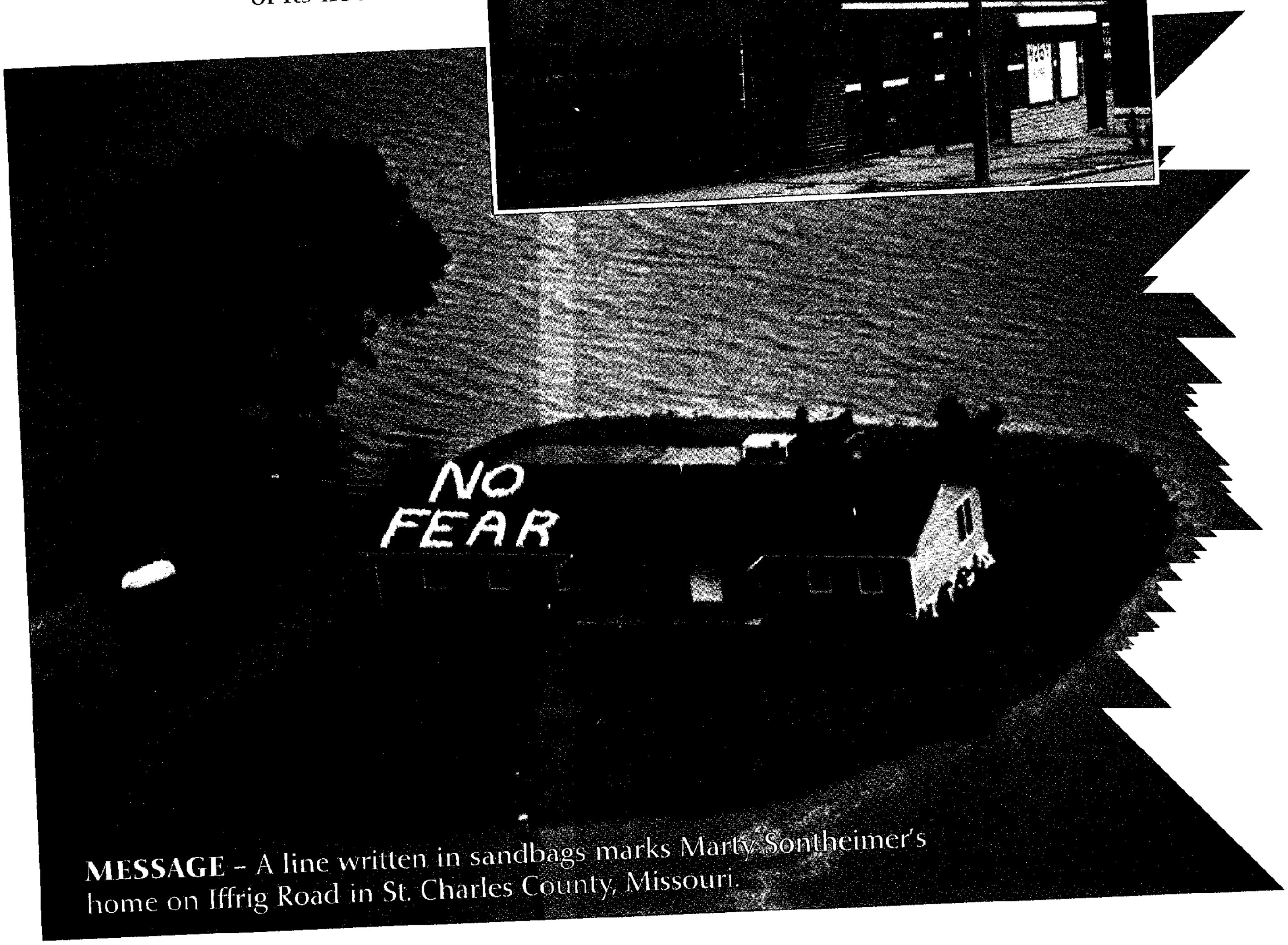
STALLED – Multicolored barges stalled in the Mississippi River near Portage des Sioux, Missouri, wait for flood waters to recede.



DEFIANT –
Ed Macarthy checks his crew's handiwork near Lemay, Missouri.

Spirit

WISHFUL - A painted sentiment north of the Missouri Botanical Garden proves that citizens of St. Louis' high and dry center are thinking of residents to the north and south of its flood wall.

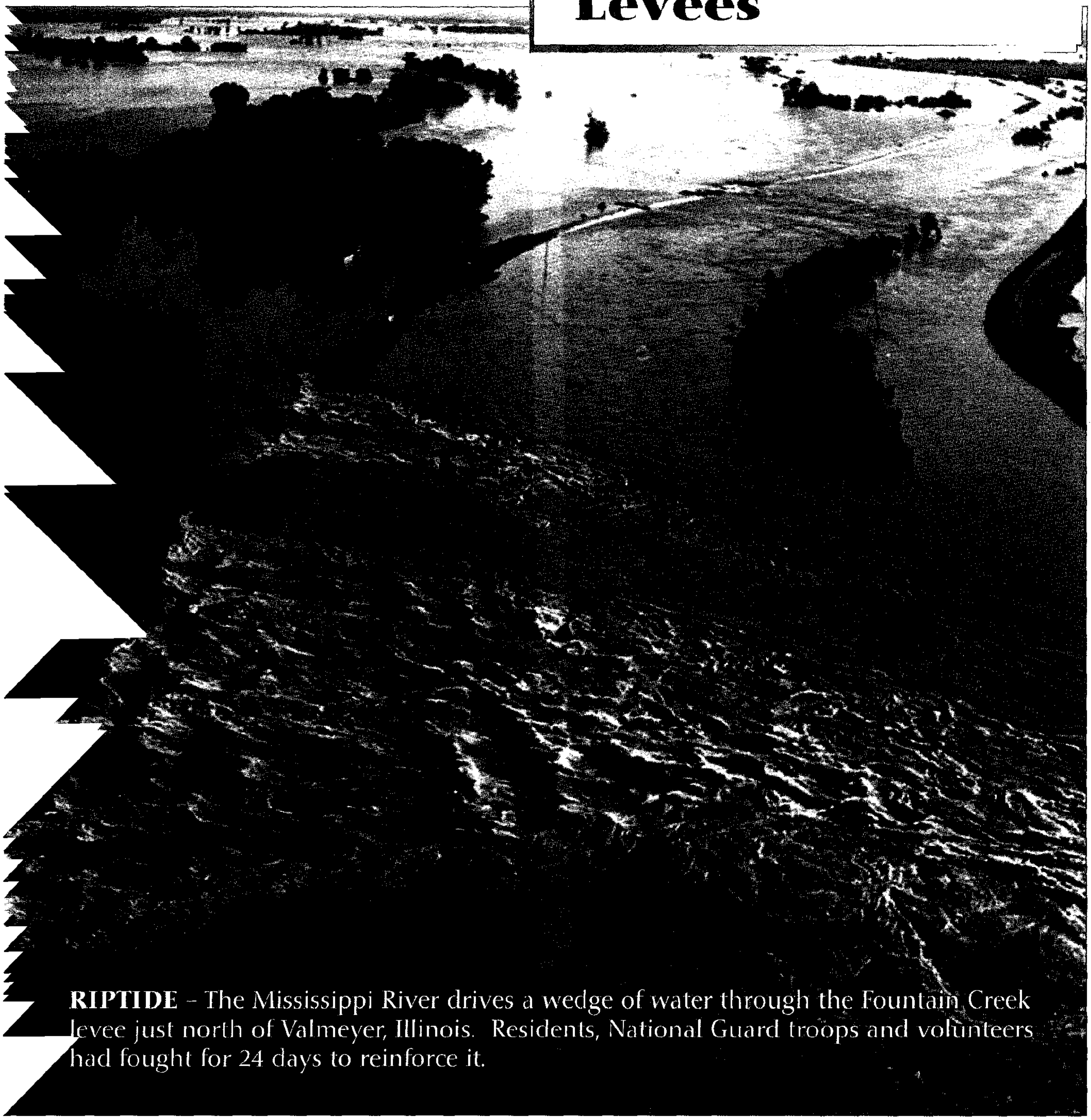


MESSAGE - A line written in sandbags marks Marty Sontheimer's home on Iffrig Road in St. Charles County, Missouri.

BATTLEGROUND – Members of the Iowa National Guard from Des Moines fortify a levee along the Des Moines River at SE 6th St. in Des Moines on July 17, 1993.

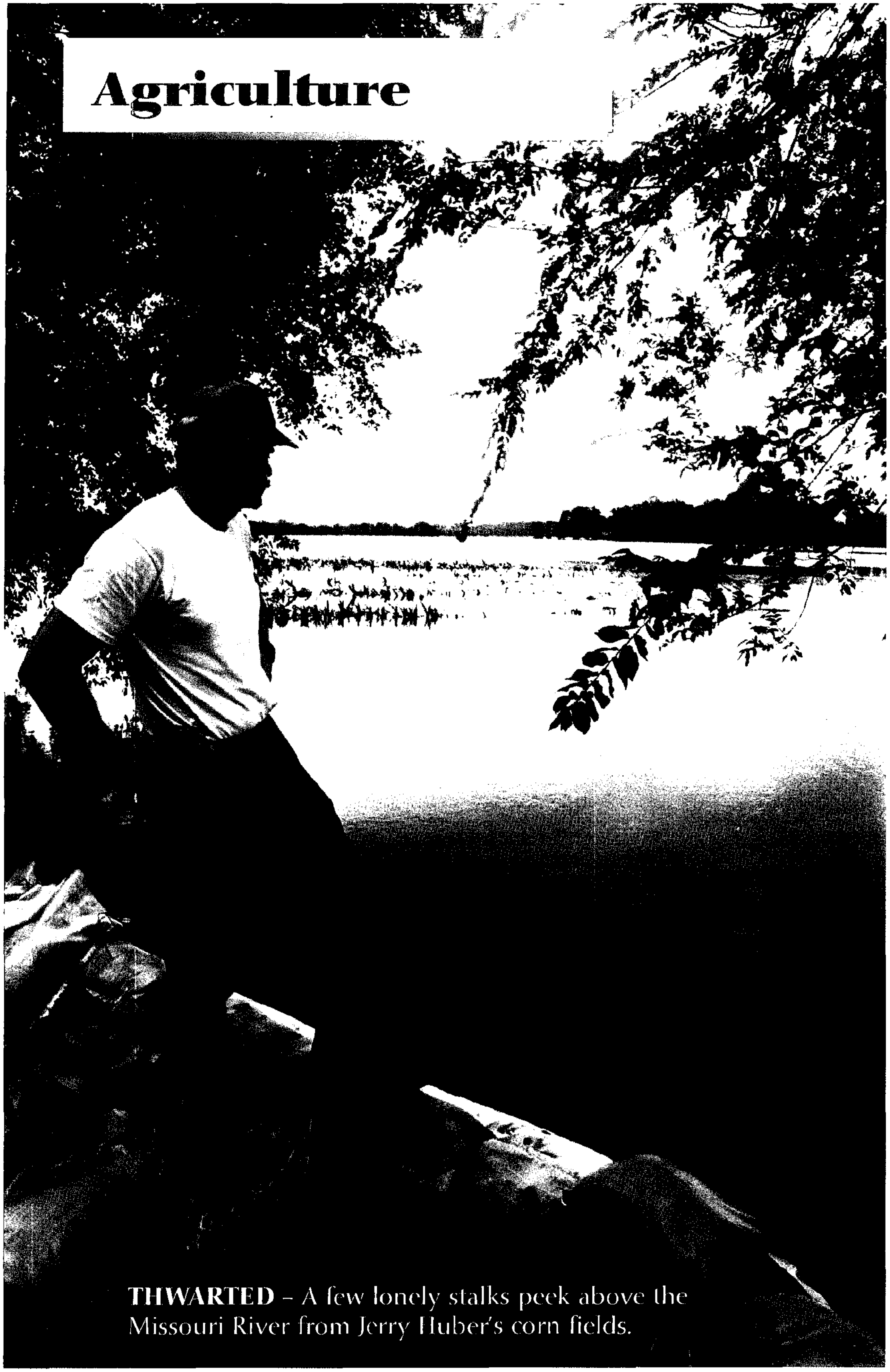
SCRAMBLING – A barge crane struggles to gouge a hole in a levee large enough to make the Army Corps Of Engineers' last-ditch plan to save Prairie du Rocher , Illinois,.work. The city was sparred.

Levees

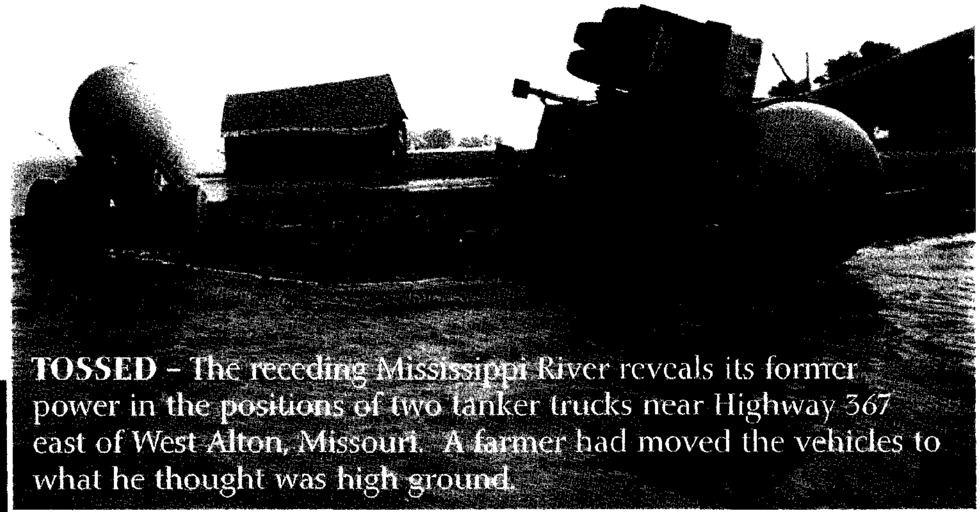


RIPTIDE – The Mississippi River drives a wedge of water through the Fountain Creek levee just north of Valmeyer, Illinois. Residents, National Guard troops and volunteers had fought for 24 days to reinforce it.

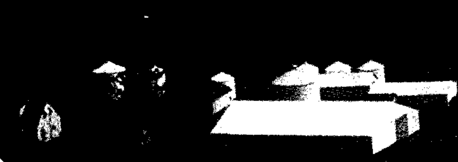
Agriculture



THWARTED – A few lonely stalks peek above the Missouri River from Jerry Huber's corn fields.



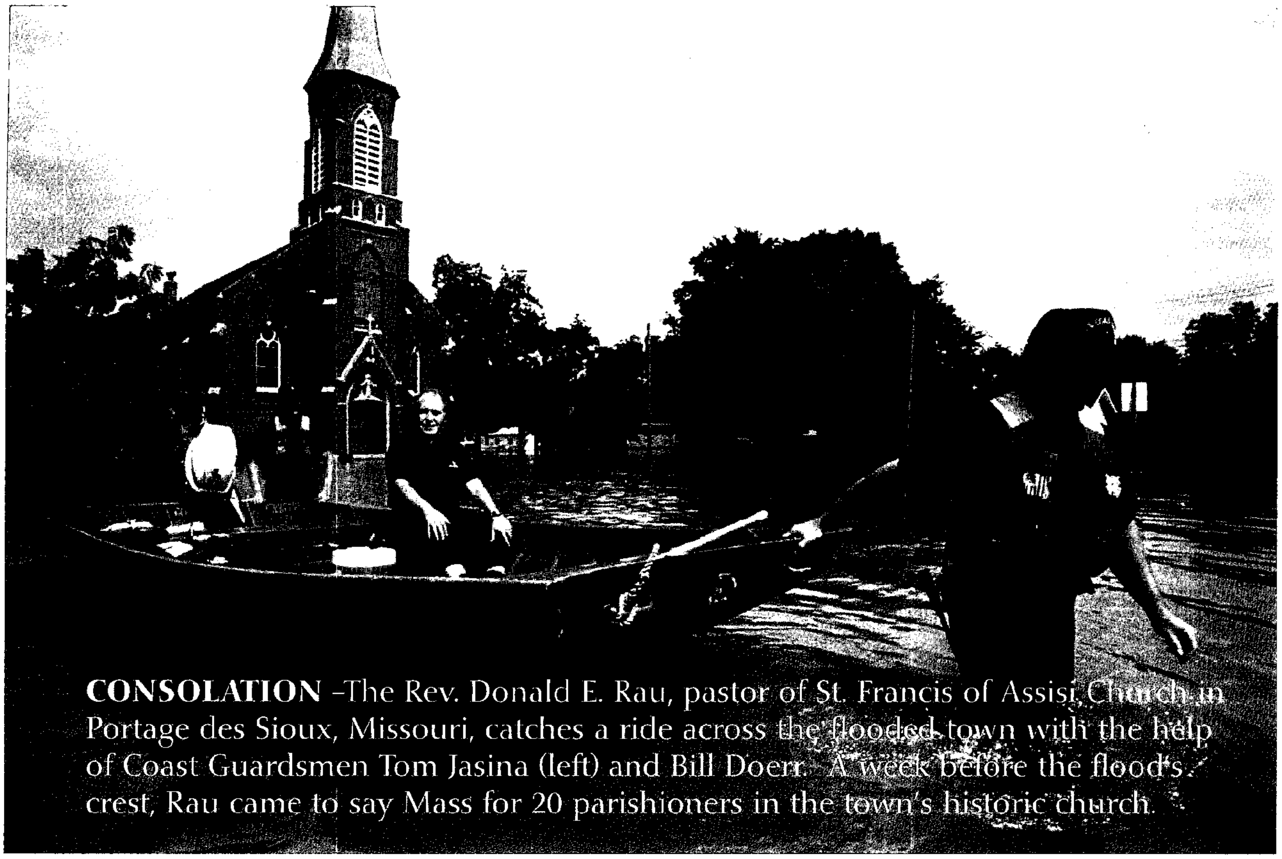
TOSSED – The receding Mississippi River reveals its former power in the positions of two tanker trucks near Highway 367 east of West Alton, Missouri. A farmer had moved the vehicles to what he thought was high ground.



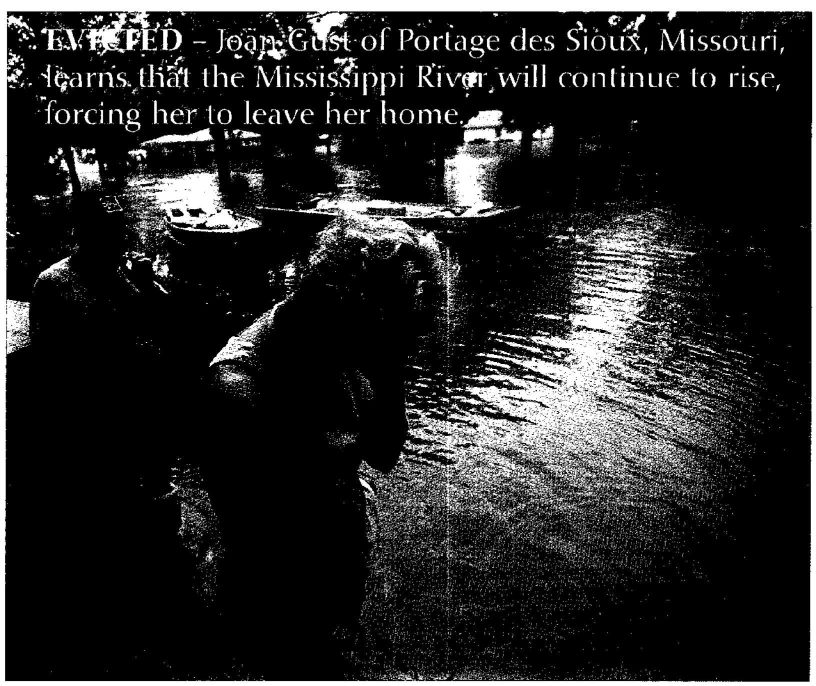
MAROONED – An inland sea surrounds a farm in north St. Charles County, Missouri, in early July, 1993. Even farmers on high ground were hurt as diseases, weeds, and insects flourished in the soaked soil and moist air.

AWASH – A farm near Winfield, Missouri, gradually loses more and more of its crop to the Mississippi River in July.

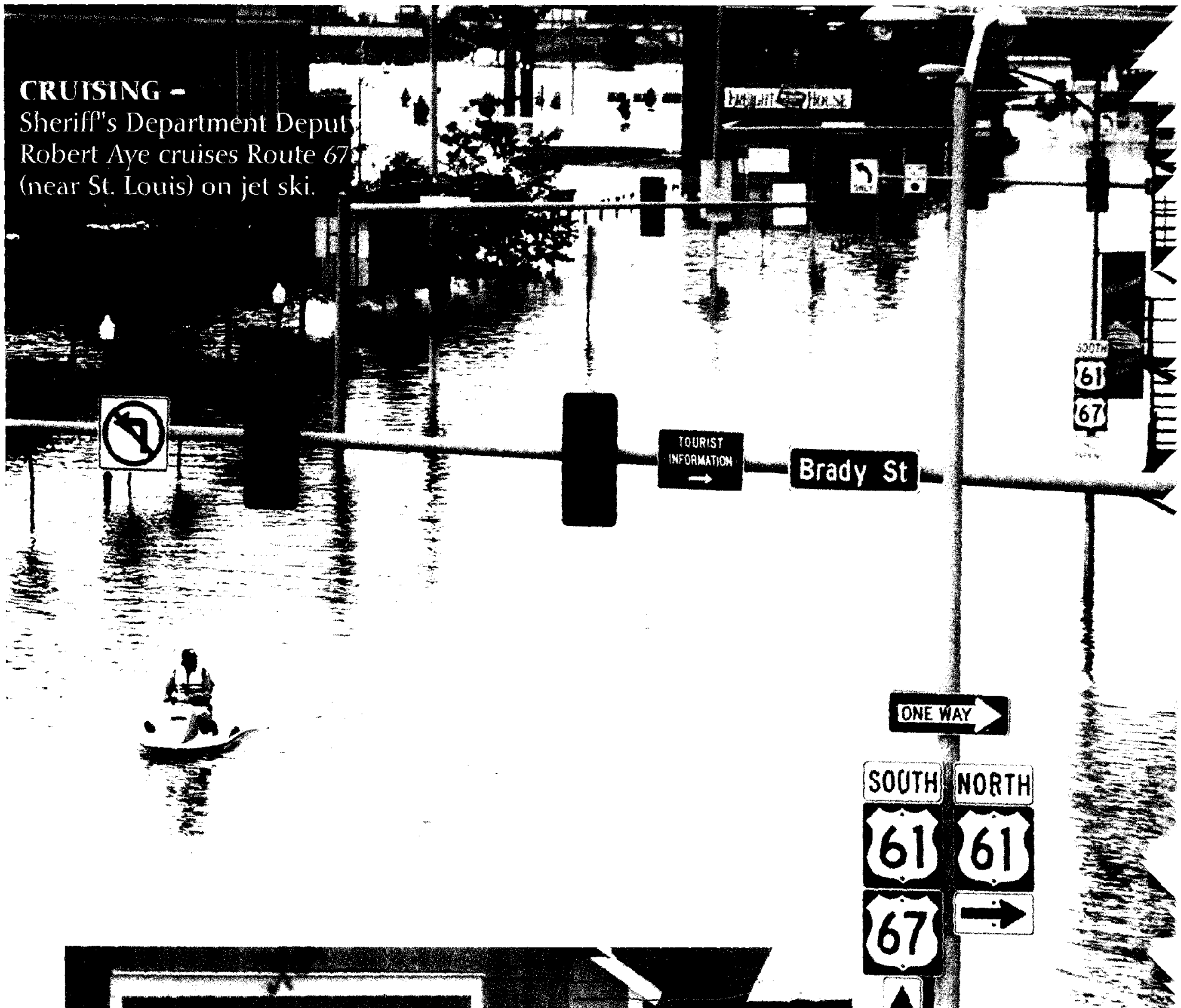
People/Impact



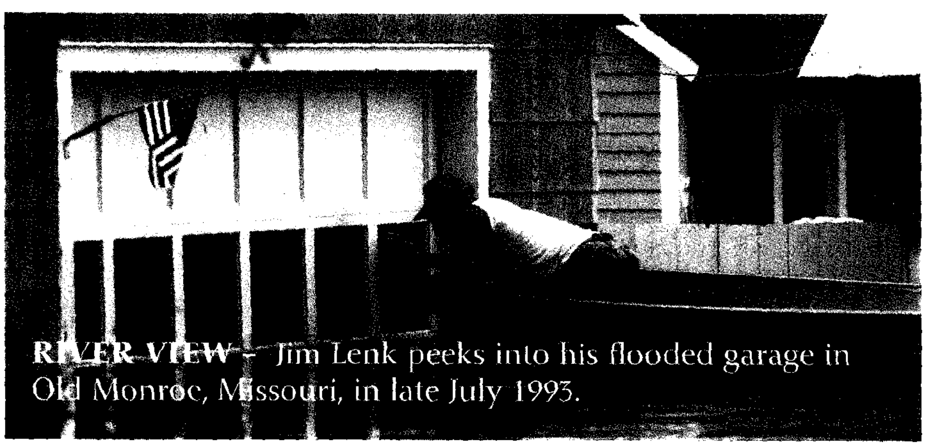
CONSOLATION –The Rev. Donald E. Rau, pastor of St. Francis of Assisi Church in Portage des Sioux, Missouri, catches a ride across the flooded town with the help of Coast Guardsmen Tom Jasina (left) and Bill Doerr. A week before the flood's crest, Rau came to say Mass for 20 parishioners in the town's historic church.



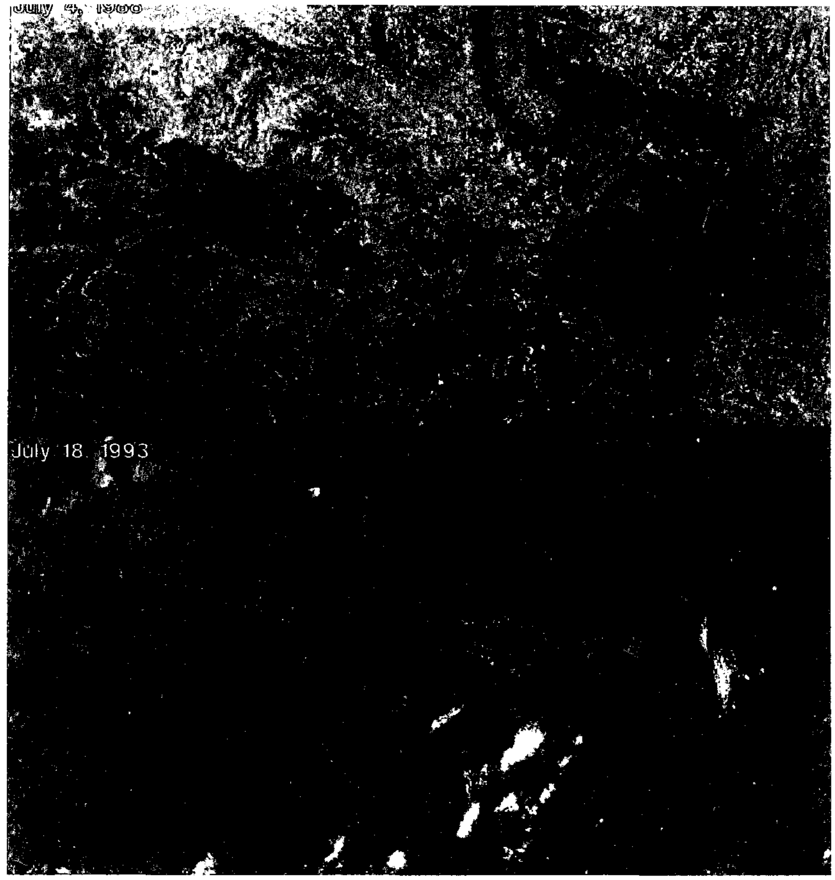
EVICTED – Joan Gust of Portage des Sioux, Missouri, learns that the Mississippi River will continue to rise, forcing her to leave her home.



CRUISING – Sheriff's Department Deputy Robert Aye cruises Route 67 (near St. Louis) on jet ski.



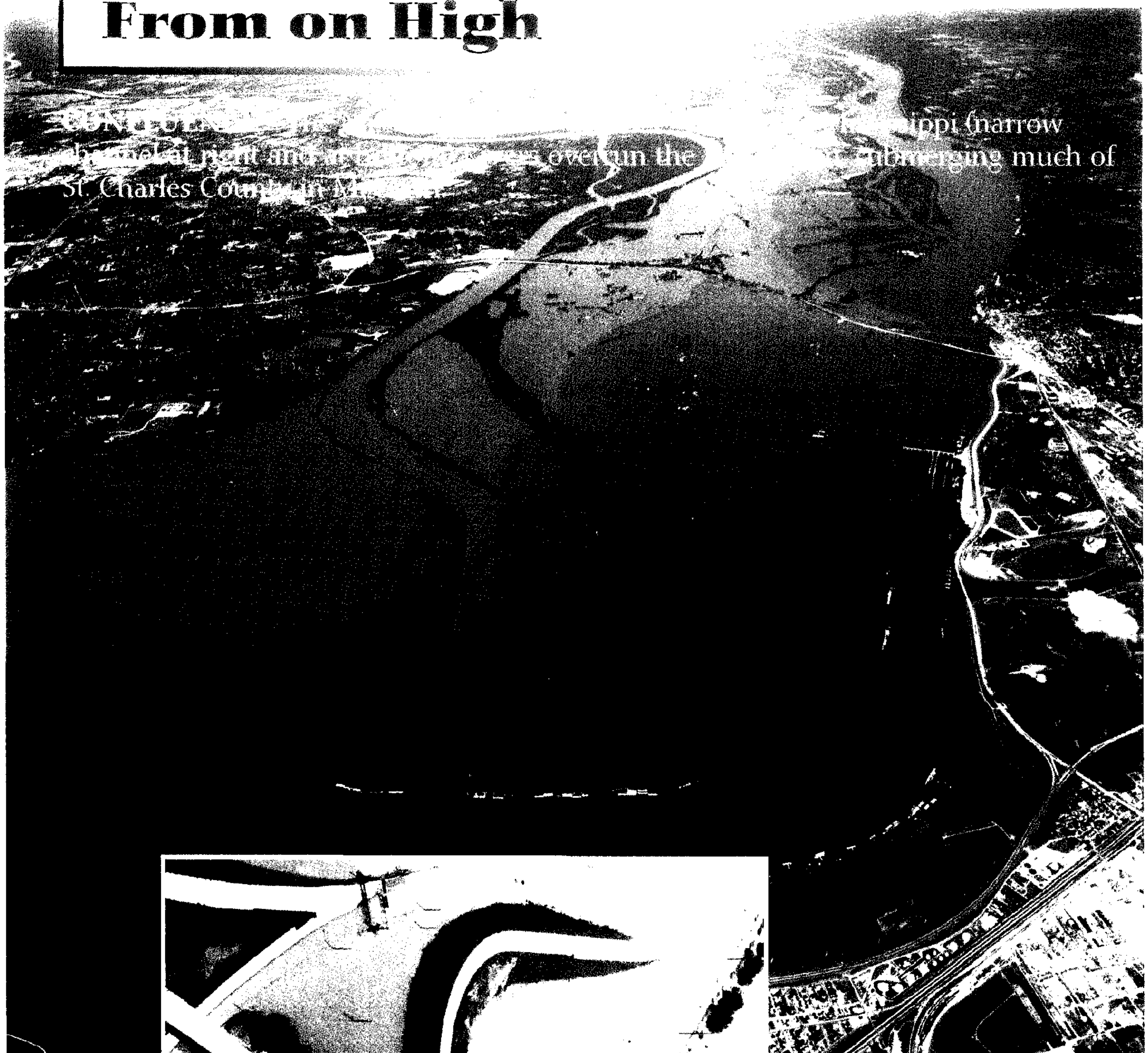
RIVER VIEW – Jim Lenk peeks into his flooded garage in Old Monroe, Missouri, in late July 1993.



CONTRAST - Landsat images of the St. Louis, Missouri area, and the confluence of the Illinois, Mississippi, and Missouri Rivers. The top image was acquired on July 4, 1988 during a severe drought. The bottom image was acquired on July 18, in the midst of The Great Flood of 1993. Vegetation is green, bare soil appears as tan, and white areas are cloud formations.

INTERSECTION - Aerial mosaic taken by NOAA aircraft on July 29, 1993, showing the confluence of the Illinois (upper-left) and Missouri Rivers (bottom-center) with the Mississippi River. Metropolitan St. Louis is visible to the left of the Mississippi River in the lower-right.

From on High



CONFLUENCE – [illegible] [illegible]sippi (narrow channel at right and [illegible] overrun the [illegible] submerging much of St. Charles County in Missouri.

BOAT RAMPS – Kansas City's interstate system was interrupted by the floodwaters.

Acknowledgements

We would like to acknowledge the gracious cooperation of the many sources listed below in providing photos used in the preceding section. In the case of copyrighted pieces, they are reprinted with permission. Except for photos explicitly identified as being provided by Federal government agencies, all photos are copyrighted and may not be reproduced without permission.

We would especially like to thank the *St. Louis Post-Dispatch* for allowing us to draw from their publication, **High and Mighty: The Flood of '93.** This single source accounted for more than half the photos included in this section. Copies of **High and Mighty** can be obtained from Andrews and McMeel, 4900 Main Street, Kansas City, Missouri 64112.

The following list identifies the sources of the preceding photos.

Front Cover

SWEPT AWAY	Jim Rackwitz, *St. Louis Post-Dispatch*
OVERPOWERED	Kevin Manning, *St. Louis Post-Dispatch*
TENUOUS TIE	Jim Rackwitz, *St. Louis Post-Dispatch*

Cities

WATERWAY	Kevin Manning, *St. Louis Post-Dispatch*
SWAMPED	Dan Ipock, *Kansas City Star*
SUBMERGED	John Sleezer, *Kansas City Star*

Water, Water, Everywhere

ENGULFED	Scott Dine, *St. Louis Post-Dispatch*

Not a Drop to Drink

ANGUISH	Jeffrey Carney, *Des Moines Register*
DRAINED	Jeff Beiermann, *Associated Press*
OVERWHELMED	Paul Griffin, Department of Defense

Inundated

SURROUNDED	Scott Dine, *St. Louis Post-Dispatch*
PROPHETIC	Tom Dietrich, NOAA
ISOLATED	Frank Robertson, *Aberdeen American News*
CLOSED	Pat Slattery, NOAA

All Creatures Great and Small

REFUGEE	Sam Leone, *St. Louis Post-Dispatch*
RECAPTURED	Odell Mitchell, Jr., *St. Louis Post-Dispatch*
CONSTERNATION	Jeffrey Carney, *Des Moines Register*

Transportation

SNAGGED	Larry Williams, *St. Louis Post-Dispatch*
WASHOUT	Jannet Walsh, *Omaha World-Herald*
LEADER	John Stennes, *Grand Forks Herald*
STALLED	Renyold Ferguson, *St. Louis Post-Dispatch*

Spirit

DEFIANT	Wes Paz, *St. Louis Post-Dispatch*
WISHFUL	Jerry Naunheim, Jr., *St. Louis Post-Dispatch*
MESSAGE	Sam Leone, *St. Louis Post-Dispatch*

Levees

BATTLEGROUND	Paul Griffin, Department of Defense
SCRAMBLING	Jerry Naunheim, Jr., *St. Louis Post-Dispatch*
RIPTIDE	Scott Dine, *St. Louis Post-Dispatch*

Agriculture

THWARTED	Sam Leone, *St. Louis Post-Dispatch*
TOSSED	Wes Paz, *St. Louis Post-Dispatch*
MAROONED	Wayne Crosslin, *St. Louis Post-Dispatch*
AWASH	Scott Dine, *St. Louis Post-Dispatch*

People/Impact

CONSOLATION	Jerry Naunheim, Jr., *St. Louis Post-Dispatch*
EVICTED	Jerry Naunheim, Jr., *St. Louis Post-Dispatch*
CRUISING	Anne Ryan, *USA Today*
RIVER VIEW	Jerry Naunheim, Jr., *St. Louis Post-Dispatch*

From on High

CONTRAST	Earth Observation Satellite Company
INTERSECTION	NOAA
CONFLUENCE	Surdex Corporation
BOAT RAMPS	*Topeka Capital Journal*

Back Cover

BEACON	Jim Rackwitz, *St. Louis Post-Dispatch*

The graphics design and layout support for the cover and photographic section of this report was provided by Sue E. Dietterle, Visual Information Specialist, Office of Public Affairs, NOAA, Rockville, Maryland.

TABLE OF CONTENTS

PROLOGUE

The U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), through the National Weather Service (NWS), has broad Federal responsibility to provide to the public severe storm and flood warnings and weather forecasts, as well as river flow and water resource forecasts. Timely and accurate forecasts and warnings of river and weather conditions are critical to protect life and property and to help support the Nation's economic and environmental well-being.

The Great Flood of 1993 constituted the most costly and devastating flood to ravage the United States in modern history. This disaster survey report on The Great Flood of 1993 that struck the Upper Midwest identifies opportunities to improve NOAA's weather and flood forecast and warning systems, not only for the affected region but also throughout the Nation. These improvements to NOAA's environmental prediction capabilities will: (1) advance the agency's overall contributions to environmental services, (2) expand the payback on current investments, and (3) improve and/or extend the benefits to many more segments of the public. An enhanced, modernized hydrologic forecast and warning system will help to achieve several of NOAA's goals and objectives as outlined in the 1995-2005 Strategic Plan that specifically include:

1. Reducing fatalities and injuries due to hazards from weather and floods,

2. Improving the flow of more accurate environmental data and predictions to the public,

3. Enhancing the ability of planners to use hydrologic forecasts in the range of days to months,

4. Providing better information for management of fresh water resources,

5. Preventing avoidable damage to private, public, and industrial property over land, in coastal areas, and along rivers, and

6. Improving efficiency, reliability, and savings in industry, transportation, agriculture, and hydro-energy systems.

Although The Great Flood of 1993 has caused devastating human, environmental, and economic impacts, the lessons learned will guide us in providing improved services and benefits to the Nation in the future.

D. James Baker
Under Secretary for Oceans and Atmosphere
and Administrator

PREFACE

The size and impact of The Great Flood of 1993 was unprecedented. Record river stages, areal extent of flooding, persons displaced, crop and property damage, and flood duration surpassed all floods in the United States in modern times. During the event, 95 forecast points in the Upper Midwest exceeded the previous floods of record, many by 6 feet or more. Approximately 500 forecast points on major rivers and tributary systems exceeded flood stage at some time during The Great Flood of 1993.

Throughout the event, the NWS generated and issued many river and flood forecasts and distributed numerous products to the public as well as to various Federal, state, and private agencies across the affected region. NOAA routinely conducts a survey of each major hydrometeorological natural disaster to assess thoroughly all aspects of its forecast and warning system including data collection and assimilation, forecast product creation and dissemination, and, ultimately, effective user response.

A NOAA disaster survey team was formed and initially met in Minneapolis, Minnesota, on Sunday, August 22, 1993. The team surveyed all aspects of the weather and flood warning and forecast systems--from data acquisition to user response--to determine the effectiveness of the NWS during the flood and to recommend any required improvements. The survey team interviewed more than 120 individuals representing more than 60 Federal, state, and private organizations across the flood-stricken region.

The consensus of opinion was clearly that the NWS provided exceptionally good services throughout this unprecedented event. As the team visited the many NWS field offices that provided hydrologic warning and forecast services to the flood-stricken area, the unparalleled human effort by NWS personnel became conspicuously apparent. NWS employees worked long hours to provide high-quality forecast products to the Upper Midwest during the prolonged flood event. The timely information contained in NWS forecast products dramatically helped to minimize the loss of life and property. Special thanks are due to the NWS employees whose conscientious efforts and dedication to excellence provided outstanding service to the Nation during The Great Flood of 1993.

This report summarizes 106 findings resulting from the survey team's investigation as well as the associated recommendations for improvement where deficiencies were found. Relevant findings and recommendations are contained in each chapter. A summary of all 106 findings and recommendations is contained in Chapter 9.

Diana H. Josephson
Diana H. Josephson
Deputy Under Secretary for Oceans and Atmosphere
and Team Leader

FOREWORD

The NOAA disaster survey team, with the support from many NWS offices, assessed the impact of The Great Flood of 1993 on the Nation and on the NWS itself. Severe flooding began in the Upper Midwest before March 1993 and continued through November 1993. The massive flooding in the region, however, occurred principally during June, July, and early August.

In August and September, after the most devastating flooding receded, the survey team visited much of the nine-state region affected by the disaster. The team visited NWS offices that provided flood warning services to the affected region. It interviewed many Federal, state, local, and private officials, as well as print and broadcast media representatives, from more than 60 different offices across the region.

This report summarizes 106 findings and recommendations that, when implemented, will improve the NWS hydrologic forecast services for the Nation in the future. The NWS will implement these recommendations whenever possible. Additionally, we will systematically track the implementation status of all appropriate recommendations to capitalize on the many lessons learned from The Great Flood of 1993.

The survey team deserves thanks for compiling the data and information and for preparing this report. The U.S. Army Corps of Engineers, the Federal Emergency Management Agency, and the Illinois State Water Survey deserve special thanks for providing expert scientists who served on the disaster survey team and who contributed valuable sections to this report. Additionally, I express the special gratitude of the NWS to the many Federal, state, and local officials and media representatives (summarized in Appendix A) who provided data, information, and insight to the survey team. In addition to assisting the survey team in its assessment of the hydrologic forecast and warning services provided by the NWS, personnel from many Federal, state, local, and private organizations served the Nation admirably during The Great Flood of 1993.

Elbert W. Friday, Jr.
Assistant Administrator
for Weather Services

DISASTER SURVEY TEAM MEMBERSHIP AND ITINERARY

1. DISASTER SURVEY TEAM AND SUPPORT PERSONNEL

Diana H. Josephson, Team Leader, Deputy Under Secretary for Oceans and Atmosphere, NOAA, Washington, D.C.

Michael D. Hudlow, Team Coordinator, Director, Office of Hydrology, NWS, Silver Spring, Maryland

Thomas R. Carroll, Technical Leader, Director, National Operational Hydrologic Remote Sensing Center, NWS, Minneapolis, Minnesota

David G. Brandon, Hydrologist in Charge, Colorado Basin River Forecast Center, NWS, Salt Lake City, Utah

Michael K. Buckley, Hydraulic Engineer, Federal Emergency Management Agency, Washington, D.C.

Stanley A. Changnon, Chief, Emeritus and Principal Scientist, Illinois State Water Survey, Champaign, Illinois

Nancy J. Eiben, Service Hydrologist, Pittsburgh Weather Service Forecast Office, NWS, Pittsburgh, Pennsylvania

Janice M. Lewis, Research Hydrologist, Office of Hydrology, NWS, Silver Spring, Maryland

Dale G. Lillie, Hydrologist in Charge, Arkansas-Red Basin River Forecast Center, NWS, Tulsa, Oklahoma

David Miskus, Meteorologist, National Meteorological Center, NWS, Camp Springs, Maryland

Roderick A. Scofield, Research Meteorologist, Physical Sciences Branch, National Environmental Satellite, Data, and Information Service, Camp Springs, Maryland

Patrick J. Slattery, Public Affairs Specialist, NOAA, NWS Central Region, Kansas City, Missouri

John J. Tebeau, Public Affairs Specialist, Office of Public Affairs, NOAA, Washington, D.C.

Dewey M. Walston, Warning and Preparedness Meteorologist, Pittsburgh Weather Service Forecast Office, NWS, Pittsburgh, Pennsylvania

Dennis R. Williams, Chief, Hydrologic Engineering Section, U.S. Army Corps of Engineers, Nashville, Tennessee

Gary R. Woodall, Warning and Coordination Meteorologist, Southern Region Headquarters, NWS, Fort Worth, Texas

In addition to the official disaster survey team, the following NOAA personnel provided critical support during the field survey and compilation of the report:

Robert K. Hartman, Development and Implementation Hydrologist, National Operational Hydrologic Remote Sensing Center, NWS, Minneapolis, Minnesota

Andrea M. Hrusovsky-Klein, Lieutenant, NOAA Corps, National Operational Hydrologic Remote Sensing Center, NWS, Minneapolis, Minnesota

Katherine L. Husnik, Hydrologic Technician, National Operational Hydrologic Remote Sensing Center, NWS, Minneapolis, Minnesota

Scott T. Kroczynski, Manager, Hydrometeorological Information Center, Office of Hydrology, NWS, Silver Spring, Maryland

Daniel M. Lipinski, Computer Programmer, National Operational Hydrologic Remote Sensing Center, NWS, Minneapolis, Minnesota

Robert W. Maxson, Lieutenant Commander, NOAA Corps, National Operational Hydrologic Remote Sensing Center, NWS, Minneapolis, Minnesota

Robert W. Poston, Lieutenant, NOAA Corps, National Operational Hydrologic Remote Sensing Center, NWS, Minneapolis, Minnesota

Frank P. Richards, Chief, Special Studies Branch, Office of Hydrology, NWS, Silver Spring, Maryland

Edward R. Johnson, Chief, Hydrologic Operations Division, Office of Hydrology, NWS, Silver Spring, Maryland

Eric Secretan, Lieutenant Commander, NOAA Corps, National Operational Hydrologic Remote Sensing Center, NWS, Minneapolis, Minnesota

Eugene A. Stallings, Chief, Hydrologic Services Branch, Office of Hydrology, NWS, Silver Spring, Maryland

The following individuals provided outstanding graphics, editorial, production, and secretarial support required to generate this disaster survey report:

Debra A. Anderson, Program Assistant, Hydrologic Systems Branch, Office of Hydrology, NWS, Silver Spring, Maryland

Cassandra Gangadhar, Secretary, Hydrologic Systems Branch, Office of Hydrology, NWS, Silver Spring, Maryland

Susan M. Gillette, Physical Science Technician, Hydrometeorological Branch, Office of Hydrology, NWS, Silver Spring, Maryland

Jennifer L. Hanson, Computer Specialist, Water Management Information Division, Office of Hydrology, NWS, Silver Spring, Maryland

Elaine A. Hauschildt, Editorial Assistant, Hydrologic Research Laboratory, Office of Hydrology, NWS, Silver Spring, Maryland

Nancy L. Helmick, Secretary, Hydrologic Services Branch, Office of Hydrology, NWS, Silver Spring, Maryland

Amy M. Hillard, Computer Clerk, Water Management Information Division, Office of Hydrology, NWS, Silver Spring, Maryland

Tonya N. Lantz, Computer Graphics Specialist, Hydrologic Research Laboratory, Office of Hydrology, NWS, Silver Spring, Maryland

Anne G. Morgan, Senior Computer Graphics Specialist, Hydrologic Research Laboratory, Office of Hydrology, NWS, Silver Spring, Maryland

Stephen L. Pond, Meteorological Technician, Special Studies Branch, Office of Hydrology, NWS, Silver Spring, Maryland

Virginia M. Radcliffe, Senior Editorial Assistant, Hydrologic Research Laboratory, Office of Hydrology, NWS, Silver Spring, Maryland

Audrey M. Sorensen, Editorial Assistant, Hydrologic Research Laboratory, Office of Hydrology, NWS, Silver Spring, Maryland

Larry A. Wenzel, Hydrometeorological Technician, Hydrologic Services Branch, Office of Hydrology, NWS, Silver Spring, Maryland

2. DISASTER SURVEY TEAM ITINERARY

The team was divided into groups so that the wide geographic area of interest across the nine-state region could be covered as efficiently as possible.

Entire Field Survey Team

August 22: (evening)

NWS National Operational Hydrologic Remote Sensing Center,
Minneapolis, Minnesota

August 23:

Minneapolis Weather Service Forecast Office (WSFO)
North Central River Forecast Center
U.S. Army Corps of Engineers, St. Paul District
Minnesota State Emergency Management Agency
KARE-TV and WCCO-TV

August 24:

Group 1a - Josephson, Hudlow, Tebeau, Lillie, Secretan, Poston

Des Moines WSFO
Des Moines City Manager
West Des Moines City Manager
WHO Radio

Group 1b - Buckley, Walston, Changnon, Maxson, Hrusovsky-Klein

Milwaukee WSFO
Chicago WSFO
Chicago Federal Emergency Management Agency

Group 2 - Carroll, Brandon, Eiben, Slattery, Williams, Lewis, Woodall

Missouri Basin River Forecast Center
Kansas City WFO
Topeka WSFO
KMBC-TV

August 25:

Group 1

Des Moines Water Works
Iowa Emergency Services Agency
Des Moines Public Works Director
Omaha WSFO
U.S. Army Corps of Engineers, Omaha District and Division Offices
KCCI-TV

Group 2

U.S. Army Corps of Engineers, Kansas City District
Columbia Weather Service Office (WSO)
Missouri State Emergency Management Agency
Boone County Emergency Management Agency
Transportation Division, Missouri Highway and
Transportation Department
Office of Railroad Safety, Division of Transportation, State of Missouri
KOMU-TV

August 26:

St. Louis Red Cross
St. Louis WSFO
KMOX Radio
St. Louis Post Dispatch
Associated Press, St. Louis
Lincoln County Sheriff, Troy, Missouri
Jersey County Sheriff, Jerseyville, Illinois
KMOV-TV

August 27:

St. Louis WSFO
Federal Aviation Administration, St. Louis
U.S. Coast Guard/U.S. Army Corps of Engineers Command Center
Congressman Jim Talent's Office
KSDK-TV
St. Louis County Police
St. Charles County Farm Bureau

August 28:

St. Charles County Emergency Management Agency

August 29:

U.S. Army Corps of Engineers, Rock Island District
(Both groups return to Minneapolis)

August 30:

Fargo WSO
Sioux Falls WSFO

EXECUTIVE SUMMARY

Unique and extreme meteorological, climatological, and hydrological conditions led to The Great Flood of 1993. The stage was set in 1992 when a wet fall resulted in above-normal soil moisture and water storage conditions in the upper Mississippi and Missouri River basins. These conditions were followed by meteorological patterns in the spring and summer months of 1993 that were more reminiscent of patterns typically experienced during the late winter and early spring months when storms often follow more northerly tracks. The persistent, repetitive nature of the storm systems, and their broad areal extent throughout the entire late spring and summer months, bombarded the Upper Midwest with copious rainfall amounts. Some areas received more than 4 feet of rain during the period.

The duration, extent, and intensity of the flooding uniquely defines this event in the 20th century. Measured in terms of economic and human impacts, The Great Flood of 1993 will be recorded as the most devastating flood in modern U.S. history. Nine states, more than 15 percent of the contiguous United States, were catastrophically impacted. Initial assessments of the economic damages of The Great Flood of 1993 indicate that losses will range between $15-20 billion, rivaling those of Hurricane Andrew. The impact of social disruption is beyond measure. Experts estimate that more than 50,000 homes were damaged or destroyed and that approximately 54,000 persons were evacuated from flooded areas.

The principal objective of the disaster survey team's assessment of the National Oceanic and Atmospheric Administration's (NOAA) services was to identify significant deficiencies, if any, in the overall hydrologic forecast and warning system and to make recommendations to improve the system. In this context, it is important to differentiate the superior performance of the National Weather Service (NWS) employees from the inherent deficiencies in the technology of the current system that, in some ways, diminish the accuracy and timeliness of today's forecast and warning services.

The performance of the NWS employees was superb. Their extraordinary and unprecedented efforts, exerted under extremely stressful conditions, continued for literally months. Their devotion to high quality services and protection of life and property was outstanding. In many cases, human judgment and expertise compensated for serious deficiencies in the current technological capabilities of the forecast and warning system. The services provided during this historic event constituted a major team effort by 3 River Forecast Centers, 9 Weather Service Forecast Offices, and 20 Weather Service Offices with support from multiple NWS national centers.

This team effort was momentous, and the collaborative effort by all offices was outstanding. Perhaps a specific illustration will help to put in perspective the dedication of NOAA employees and their human contributions to the forecasting for this cataclysmic event: One of the hydrologic forecasters at 2 a.m., unable to sleep, realized he was uneasy about the latest river stage forecast for St. Louis. After days of extended hours of duty, the forecaster got up, took a shower, and returned to the River Forecast Center (RFC) to examine additional information and to further confer with his colleagues. After considerable debate, this forecaster convinced himself and other staff members that the forecast stage at St. Louis should be raised. In retrospect, the decision was correct and consequently resulted in significantly improved mitigation actions. Arriving at a decision to change a forecast of this importance is stressful and places the forecaster in an extremely lonely position when he/she knows that the ultimate decision will likely impact directly on life and property. This anecdote epitomizes the dedication of the men and women on the NOAA team and is only one illustration of the countless, magnanimous efforts made throughout the event.

By and large, most of the deficiencies identified by the NOAA survey team resulted from inadequate technological capabilities within the current forecast and warning system. In large measure, the identified deficiencies can be corrected through implementation of more advanced hydrologic prediction capabilities. A substantial number of these deficiencies will be corrected as part of modernization and associated restructuring (MAR) of the NWS. In fact, a major recommendation of the team is that MAR must be maintained on schedule or accelerated wherever possible. The modernization has progressed to the point that limited benefits were clearly capitalized upon during The Great Flood of 1993.

The installed base of Weather Surveillance Radar 88 Doppler (WSR-88D) systems under MAR provided major benefits during the flood event. At least two specific instances were documented in which radar rainfall estimates from the Chicago and Kansas City WSR-88D systems saved lives during flash flood conditions on July 18, 1993, and on August 11-12, 1993, respectively. Maximum use of WSR-88D data for hydrologic forecast and warnings, however, awaits completion of the Next Generation Weather Radar (NEXRAD--now called the WSR-88D) network over the upper Mississippi River basin. In addition, Advanced Weather Interactive Processing System (AWIPS), or AWIPS-type capability under MAR, is needed at the RFCs to process and mosaic the information from multiple radars in their areas of forecast responsibility. Such capabilities are currently being implemented as part of the AWIPS contract at the Missouri Basin RFC at Kansas City, Missouri. It is important to implement similar capabilities at the North Central RFC in Minneapolis, Minnesota, in preparation for the high potential of spring snowmelt flooding in 1994.

Of equal importance to the technological enhancements are the advances in human resources also planned as part of MAR. These include training on modernized NWS technology and advanced hydrometeorological functions as part of the RFC operations. These new RFC hydrometeorological capabilities will facilitate the closer coupling of meteorological and hydrological operations required to effectively include quantitative precipitation forecasts and climate information in the hydrologic prediction models.

Other elements needed to improve deficiencies beyond those addressed by MAR include substantial advances in NOAA's capabilities to model and to predict the complex hydrologic and hydraulic conditions experienced in the Missouri and Mississippi River basins during The Great Flood of 1993. Prediction of streamflow conditions on these major rivers and tributaries requires the best possible physical representation of all phases of the water cycle. This includes proper accounting for soil moisture conditions, levee effects, and transport of water through complex river channels, reservoirs, and locks and dams. In addition, achieving the greatest forecast and warning accuracy, with the longest lead-times possible, requires incorporation of future meteorological and climatological forecasts, especially the incorporation of future rainfall estimates in the forecast methodology. Finally, hydrologic forecasts require greater quantification that includes bracketed confidence limits, or associated probabilities, that provide likelihood of occurrences for a range of specific stage forecasts. These more specific and timely forecasts would enable emergency managers and water facility operators to make more accurate, precise, and informed decisions required to carry out their routine operations and emergency flood mitigation actions effectively.

The Department of Commerce and NOAA are committed to develop and to implement an advanced hydrologic prediction system for the entire Nation. This activity constitutes a major component of the NOAA 1995-2005 Strategic Plan to improve NOAA's role in environmental prediction. Part of this effort clearly will be critically dependent on major collaborative efforts with many of NOAA's partners at the Federal, state, and local levels, as well as in the academic and the private sectors. Improvements in the Nation's capabilities to predict more accurately the hydrologic extremes of droughts and floods, as well as to provide day-to-day information for improved water management decisions, will translate into enormous economic and environmental benefits for the Nation. Improved decision-making information for The Great Flood of 1993 alone could have easily translated into savings of hundreds of millions of dollars through improved mitigation actions. Moreover, the associated human suffering could have been dramatically reduced with more timely, accurate, and improved decision-making information.

Other areas of deficiency identified by the survey team in the overall prediction and response system included inadequate computer processing and telecommunications capabilities, as well as problems associated with timely and complete dissemination of appropriate products. Any single forecast is of value only if it is disseminated in a timely fashion and appropriate actions are taken. During The Great Flood of 1993, effective communication of critical information was inadequate on several occasions. In other instances, conflicting communications and the absence of suitable preparedness response plans by local officials hampered mitigation actions. The findings and recommendations pertaining to these and other areas of concern are contained in the relevant chapters of this report. Also, for ease of reference, all 106 findings and recommendations are consolidated in Chapter 9.

In conclusion, it is clear that appropriate actions should be taken in the short term to strengthen the hydrologic service capabilities of the NWS and to prepare for the potentially devastating spring floods that may develop in 1994 over precisely the same region of the country impacted by The Great Flood of 1993. Moreover, it is imperative that, over the longer term, NOAA take systematic actions to capitalize on the NWS MAR and on the proven, advanced hydrologic prediction capabilities required to improve NOAA's services during future flood and drought events. More detailed findings and recommendations to seize on opportunities for improvements based on lessons learned from The Great Flood of 1993 are contained in Chapter 2 of this report. Additionally, the impacts; the hydrometeorological setting; the hydrologic and hydraulic forecast methodology; the data acquisition, telecommunications, facilities, and computer systems; the warning and forecast services; the coordination and dissemination; and the preparedness and user-response issues related to The Great Flood of 1993 are discussed in considerable detail in Chapters 1, 3, 4, 5, 6, 7, and 8, respectively.

ABBREVIATIONS AND ACRONYMS

ABRFC	Arkansas-Red Basin River Forecast Center
AFOS	Automation of Field Operations and Services
AHPS	Advanced Hydrologic Prediction System
ALERT	Automated Local Evaluation in Real-Time
API	Antecedent Precipitation Index
API-CIN	Ohio RFC Antecedent Precipitation Index Rainfall-Runoff Model
API-CONT	Continuous Antecedent Precipitation Index
API-HAR	Middle Atlantic RFC Antecedent Precipitation Index Rainfall-Runoff Model
API-MKC	Central Region Antecedent Precipitation Index Rainfall-Runoff Model
API-SLC	Colorado RFC Antecedent Precipitation Index Rainfall-Runoff Model
ASOS	Automated Surface Observing System
AVHRR	Advanced Very High Resolution Radiometer (NOAA)
AWIPS	Advanced Weather Interactive Processing System
BASEFLOW	Baseflow Generation Runoff Model
BIS	Bismarck WSFO
BON	Boonville river forecast point (MBRFC)
BUR	Burlington river forecast point (NCRFC)
CAC	Climate Analysis Center (NMC)
CADAS	Centralized Automatic Data Acquisition System
CHANLOSS	Channel Loss Routing Model
CHI	Former designation for Chicago WSFO (now LOT)
CHS	Chester river forecast point (NCRFC)
COE	U.S. Army Corps of Engineers
CRT	Cathode Ray Tube (computer monitor)
DAC	Disaster Application Centers
DCP	Data Collection Platform
DFO	Disaster Field Office
DMSP	Defense Meteorological Satellite Program
DOC	Department of Commerce
DSM	Des Moines WSFO
DWOPER	Operational Dynamic Wave Routing Model
D24	Dam 24 river forecast point (NCRFC)
EMA	Emergency Management Agency
ENSO	El Niño/Southern Oscillation
EOC	Emergency Operations Center
E-19	river forecast point description

FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FFA	Flash Flood Watch
FFP	Flash Flood Potential
FFS	Flash Flood Statement
FFW	Flash Flood Warning
FLS	Flood Statement
FLW	Flood Warning
FSD	Sioux Falls WSFO
GIS	Geographic Information System
GOES	Geostationary Operational Environmental Satellite
GRF	Grafton river forecast point (NCRFC)
GUT	Guttenburg river forecast point (NCRFC)
HADS	Hydrometeorological Automated Data System
HAS	Hydrometeorological Analysis and Support
HEM	Hermann river forecast point (MBRFC)
HIC	Hydrologist in Charge
HRL	Hydrologic Research Laboratory (OH)
HSA	Hydrologic Service Area
IFFA	Interactive Flash Flood Analyzer
LAC	LaCrosse river forecast point (NCRFC)
LAG/K	Lag and K Routing Model
LARC	Limited Automatic Remote Collector
LAY/COEF	Layered Coefficient Routing Model
LFWS	Local Flood Warning System
LMRFC	Lower Mississippi River Forecast Center (Slidell, Louisiana)
MAP	mean areal precipitation
MAR	modernization and associated restructuring
MBRFC	Missouri Basin River Forecast Center (Kansas City)
MCI	Kansas City WSO
MCS	Mesoscale Convective System
MIC	Meteorologist in Charge
MKE	Milwaukee WSO
MOD	Meteorological Operations Division (NMC)
MSP	Minneapolis WSFO
MUSKROUT	Muskingum Routing Model
MW	microwave
NCCF	NOAA Central Computer Facility
NCRFC	North Central River Forecast Center (Minneapolis)
NESDIS	National Environmental Satellite, Data, and Information Service (NOAA)
NEXRAD	Next Generation Weather Radar
NIDS	NEXRAD Information Dissemination System
NMC	National Meteorological Center (NWS)
NOAA	National Oceanic and Atmospheric Administration

NOHRSC	National Operational Hydrologic Remote Sensing Center (NWS)
NPPU	National Precipitation Prediction Unit
NWR	NOAA Weather Radio
NWS	National Weather Service
NWSRFS	NWS River Forecast System
NWWS	NOAA Weather Wire Service
OH	Office of Hydrology (NWS)
OM	Office of Meteorology (NWS)
OVN	Omaha WSFO
PDI	Palmer Drought Index
PUP	Principle User Processor (WSR-88D)
QPF	Quantitative Precipitation Forecast
raob	radiosonde observation
RCC	Regional Climate Center
RES-SINGL	Single Reservoir Simulation Routing Model
RFC	River Forecast Center (NWS)
RJE	remote job entry
ROSA	Remote Observation System Automation
RVA	River Summary
RVS	River Statement
SAB	Synoptic Analysis Branch (NESDIS)
SAC-SMA	Sacramento Soil Moisture Accounting Runoff Model
SH	Service Hydrologist
SHEF	Standard Hydrometeorological Exchange Format
SHIMS	Service Hydrologist Information Management System
SNOW-17	NWSRFS snow accumulation and melt runoff model
SPS	Special Weather Statement
SRWARN	Southern Region Warn (a computer program)
SSM/I	Special Sensor Microwave/Imager
SST	sea surface temperature
STAGE-Q	Stage-Discharge Conversion Model
STL	former designation for St Louis WSFO (now LSX)
STP	St Paul river forecast point (NCRFC)
SVR	Severe Thunderstorm Warning
SVS	Severe Weather Statement
SXC	Sioux City river forecast point (MBRFC)
TATUM	Tatum Routing Model
TIR	thermal infrared
TM	thematic mapper
TOP	Topeka WSFO
TOR	Tornado Warning
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTC	Universal Coordinated Time

VDUC	VAS Data Utilization Computer
VIS	visible
WARFS	Water Resources Forecasting System
WCM	Warning and Coordination Meteorologist
WGRFC	West Gulf River Forecast Center
WPM	Warning and Preparedness Meteorologist
WFO	Weather Forecast Office
WSFO	Weather Service Forecast Office
WSO	Weather Service Office
WSR-57	Weather Surveillance Radar 1957
WSR-88D	Weather Surveillance Radar 1988 Doppler
XIN-SMA	Xinanjiang Soil Moisture Accounting Runoff Model

CHAPTER 1

GENERAL DESCRIPTION OF THE EVENT AND ITS IMPACT

1.1 INTRODUCTION

The Great Flood of 1993 was an unprecedented hydrometeorological event since the United States started to provide weather services in the mid-1800s. In terms of precipitation amounts, record river stages, areal extent of flooding, persons displaced, crop and property damage, and flood duration, this event (or sequence of events) surpassed all floods in the United States during modern times. The purpose of this chapter is to provide a cursory overview of The Great Flood of 1993 and some of its impacts. Its contents are by no means all-inclusive. Full meteorologic and hydrologic analyses of this event, as well as a complete study of the flood impacts, will be the subject of many reports and studies conducted by Federal, state, and private agencies for years to come.

Record and near-record precipitation during the spring of 1993, on soil saturated from previous seasonal precipitation, resulted in flooding along many of the major river systems and their tributaries in the Upper Midwest. Rivers climbed above flood stage at approximately 500 forecast points in the nine-state region. Moreover, record flooding occurred at 95 forecast points in the Upper Midwest during the summer of 1993. Flood records were broken at 44 forecast points on the upper Mississippi River system, at 49 forecast points on the Missouri River system, and at 2 forecast points on the Red River of the North system. Within the Mississippi River system, 1993 floods of record include those set at 15 forecast points on the main stem, at 4 forecast points on the Iowa River, at 5 forecast points on the Des Moines River, and at 2 forecast points on the Raccoon River.

Within the Missouri River system, 1993 floods of record include those set at 14 forecast points on the main stem and at 4 forecast points on each of the Saline, Smoky Hill, and Grand Rivers. During the event, near flood of record stage occurred at an additional 23 forecast points on the Missouri River system alone. Record flood stages surpassed old record stages by more than 6 feet in some cases. For example, in 1993, flood records set more than 42 years ago on the main stem of the Missouri were broken by more than 4 feet at multiple forecast points. In at least one case, a new flood of record was established early in the event only to be broken by higher water later in the event. The historic flood of record on the Mississippi at St. Louis was established on April 28, 1973, at 43.2 feet; reestablished on July 21, 1993, with a flood stage of 46.9 feet; and reestablished again 11 days later on August 1, 1993, with a record flood stage of 49.58 feet. Figure 1-1 gives an overview of the areal extent of The Great Flood of 1993.

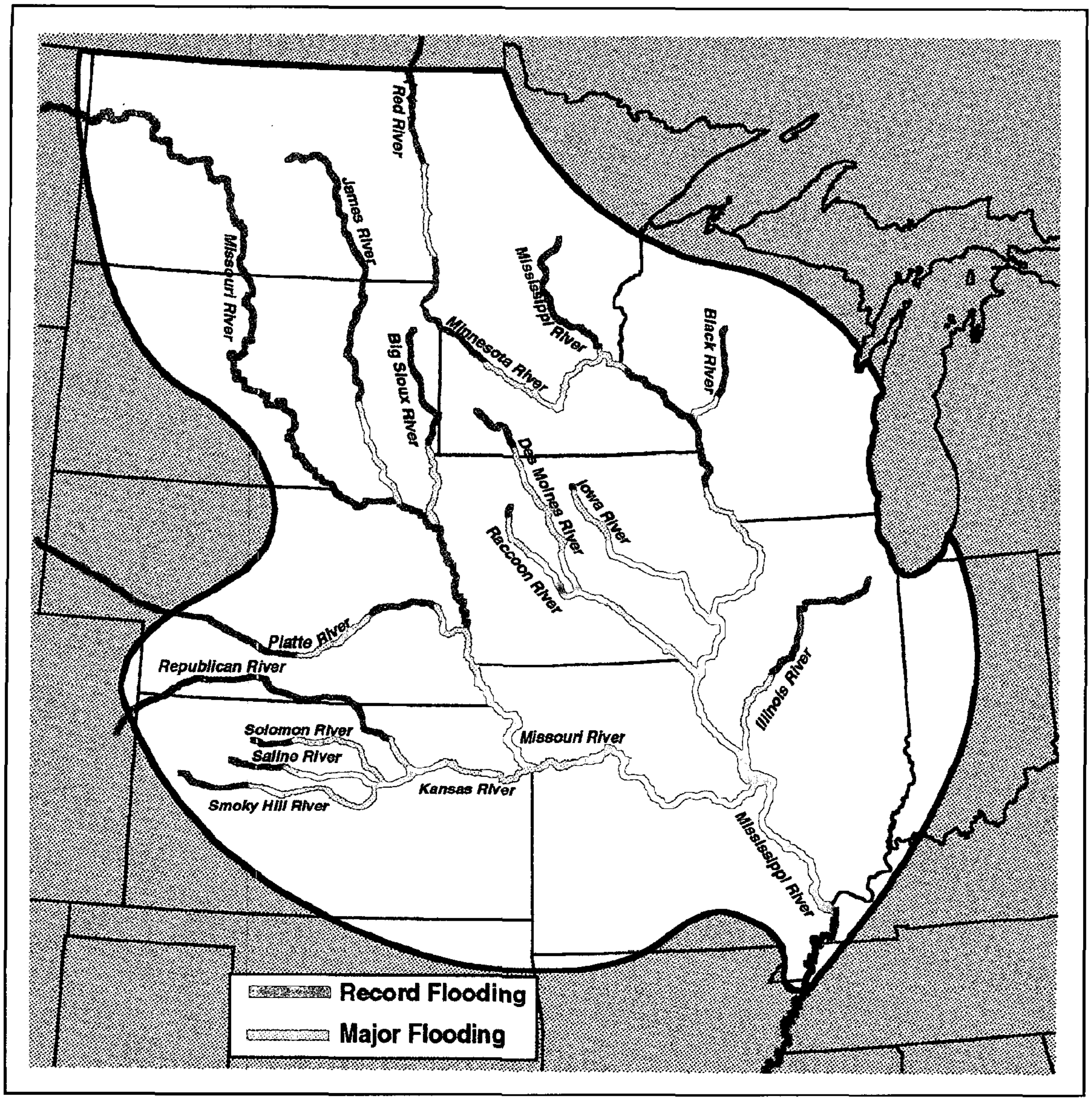


Figure 1-1. *General area impacted by heavy rainfall and/or flooding during The Great Flood of 1993.*

The duration of The Great Flood of 1993 was as overwhelming as the areal extent of flooding and the number of record stages established. Spring flooding began in March as a result of a previous wet fall, normal to above-normal snow accumulation, and rapid spring snowmelt accompanied by heavy spring rainfall. On May 8, record flooding occurred in South Dakota on Split Rock Creek at Corson and in Minnesota on the Rock River at Luverne. On May 22-24, heavy thunderstorms produced 3-7 inches of rain in 3 hours over Sioux Falls resulting in major urban and residential flooding across the city. The Big Sioux and Vermillion Rivers in

South Dakota went above flood stage in late May and remained in flood through mid-June. Major flooding continued throughout the summer along the Missouri and Mississippi Rivers. For example, on September 1, 1993, the towns of Hannibal, Louisiana, and Clarksville, Missouri, had experienced 153 consecutive days of flooding. Flooding at levels above flood stage continued through the middle of September in many regions along the Mississippi River.

The duration and magnitude of The Great Flood of 1993, as well as its antecedent conditions, strongly support the premise that this event was a significant climate variation rather than simply a sequence of meteorological events. It is quite possible that one or more climate-driving forces (e.g., El Niño/Southern Oscillation) significantly contributed to this climate variation. A more thorough analysis of this situation is expected to result in improved understanding of the roles contributing factors may have played.

1.2 INTERAGENCY FLOOD RESPONSE

The forecasting services provided by the National Weather Service (NWS) is but one of many activities undertaken by the Federal Government in responding to The Great Flood of 1993. The high quality and timeliness of these forecasts were critical to the success of evacuation and emergency mitigation actions initiated at all levels of government, as well as by voluntary groups and private citizens. The Federal Response Plan was signed by 26 Federal departments and agencies, who participated in a coordinated effort to address the basic needs for the victims of The Great Flood of 1993. Nearly 4,000 Federal personnel from the various Federal agencies were committed to assist in the response activities. Two major Federal contributors to the response operations included the U.S. Army Corps of Engineers (COE) and the Federal Emergency Management Agency (FEMA).

The COE provided technical assistance to states and local authorities to prevent loss of life and property damage during The Great Flood of 1993. In addition, the COE maintained and operated navigation and flood control facilities on the flooded river systems. Response and recovery assistance was provided by the COE under two laws, Public Law 84-99 and Public Law 93-288 (Stafford Act). The COE received $20 million from FEMA to supply emergency sanitary and water supply facilities, bridge and pier inspections, damage survey report, and other technical support to local authorities. In addition, the COE distributed more than 31 million sand bags and more than 400 water pumps. At the height of the flood, the COE committed 800 personnel to these efforts. The COE and FEMA worked together to evacuate flood water in low areas and impounded behind levees, to remove debris, and to restore public facilities.

With the first Federal disaster declaration issued on June 11, 1993, for several counties in Minnesota, FEMA immediately mobilized response and recovery operations authorized under the Stafford Act (Public Law 93-288). This initial response included the establishment of a Disaster Field Office (DFO) which coordinated the operations in the affected areas, and several Disaster Application Centers (DAC) where applications for individual assistance were processed. At the peak of the response operations, FEMA had established 11 DFOs and numerous DACs throughout the affected areas, in addition to operating a tele-registration 800 hot line to provide information and to receive applications from those unable to make it to one of the DACs. At the time of this writing, over 120,000 registrations for disaster assistance have been accepted from flood victims totaling more than $150 million in payments. Another $200 million has been paid from premiums collected under the National Flood Insurance Program for flood damage to insured property.

1.3 IMPACT OF THE FLOODING

The Great Flood of 1993 caused enormous human suffering. At least 75 towns were completely inundated, some of which may never be rebuilt. Many people worked 24 hours a day for weeks building up levees to ward off the flood, only to have these levees eventually fail. The flood destroyed family businesses, community schools, people's homes and property, and treasures of their heritage. In Hardin, Missouri, more than 700 coffins were washed out of grave sites, many of which have not been recovered.

More than 20 million acres of land in nine states were inundated by The Great Flood of 1993. The entire state of Iowa was designated as a Federal disaster area. Large sections of eight other states--North Dakota, South Dakota, Minnesota, Wisconsin, Illinois, Missouri, Nebraska, and Kansas--were also declared Federal disaster areas. The number of fatalities caused by the flood is estimated to be 48 people. Approximately 54,000 people had to be evacuated from flooded areas at some time during the flood, and 50,000 homes with associated property were estimated to be destroyed or damaged. The flood also had enormous ongoing, indirect impacts on hundreds of thousands of people. In Iowa, for example, tens of thousands of people were unable to work because of a lack of public water supplies needed for sanitation, fire fighting, or routine operation of businesses. Barge, rail, and truck traffic was curtailed or completely halted in many areas.

Initial assessments of the economic impact of The Great Flood of 1993 indicate that losses will range between $15-20 billion. This damage estimate may prove to be too low as the flood continues to recede, exposing additional previously unknown destruction. In terms of interstate commerce alone, the flood has had dramatic impact. The towing industry estimates that at least $3-4 million was lost each day that the Mississippi River was closed to barge traffic. The trucking industry was forced to reroute much of its traffic to more lengthy routes due to the many interstate highway and local bridge closures. At different times during the flood, all bridges from Davenport, Iowa, to St. Louis, Missouri, on the Mississippi River, and all bridges from Kansas City, Missouri, to St. Louis on the Missouri River, were closed. Sections of Interstate Highways I-35, I-70, and I-29, as well as hundreds of miles of secondary roads, were also closed.

Numerous miles of railroad track were flooded, halting rail transit along many rail systems. Furthermore, the flow of flood waters eroded the rail beds, and it will require significant funds to return these tracks to operation. At one time, seven of the eight rail lines across the state of Missouri were closed to rail traffic. It has been estimated that the rail industry suffered operating losses in excess of $300 million loss and $100 million in flood damages in Missouri alone. Finally, 12 commercial airports were closed by the flood, including the Spirit of St. Louis Airport, which is a major executive airfield located in Chesterfield, Missouri.

Locks, dams, and levees on the affected river systems must all be inspected and repaired in the aftermath of the flood. Approximately 6,000 miles of non-Federal levees protect cities, towns, and farm land along many of the major rivers affected by the flood. The COE reports that 40 of 229 Federal levees and 1,043 of 1,347 non-Federal levees were overtopped or damaged during the flood. Damage to locks and dams will be fully assessed only after the rivers fall well below flood stage. The major courses and beds of the rivers themselves may be significantly altered as a result of the flood that will affect future river navigation and commerce.

The agriculture industry experienced major economic losses as a direct result of The Great Flood of 1993. In large areas inundated by the flood, the harvest of 1993 was a total loss. More than 600 billion tons of topsoil erosion by the river flow and vast deposits of sand and silt on farm land will have long-term impacts on future farm productivity. Much of the soil removed from agricultural land has been deposited in the major rivers and may affect the flora and fauna that form the various river ecosystems. Pollutants and raw sewage released as the flood spread inland will cause additional stress on the river environment.

The Great Flood of 1993 began well before the devastating flooding that occurred during June, July, and early August. Moreover, disastrous flooding continued in the late summer and fall across portions of the Upper Midwest. This report, however, focuses on the forecasts and services provided by the NWS during June, July, and early August when the most catastrophic flooding occurred across the region. Nonetheless, late-summer and fall flooding was quite significant. One example occurred on August 29, 1993, when the city of Des Moines, Iowa, received enough precipitation to force once more thousands of people out of homes to which they had recently returned in the aftermath of previous flooding. Above-normal fall soil moisture conditions provide serious potential for new flooding should significant rainfall occur. Fall soil moisture conditions coupled with normal snow accumulation and spring precipitation help constitute a significant threat of major spring snowmelt flooding across the Upper Midwest in 1994.

CHAPTER 2

MAJOR LESSONS LEARNED AND OPPORTUNITIES FOR THE FUTURE

2.1 INTRODUCTION

The unique meteorological, climatological, hydrological, and hydraulic conditions that led to The Great Flood of 1993 provide many lessons that can lead to future improvements in the services provided by the National Weather Service (NWS). All aspects of the performance of the NWS river forecast and warning system were evaluated as part of the field survey.

Almost all the findings and associated recommendations stem from lessons learned and point toward refinements for the future. The purpose of this chapter is to highlight some of the more fundamental, global findings and recommendations.

2.2 SCOPE AND BENEFITS OF THE NATIONAL WEATHER SERVICE RESPONSE

As illustrated in Figure 1-1, the area impacted by flooding covered major portions of nine states. This area, comprising approximately 15 percent of the 48 contiguous states, contains 2 River Forecast Centers (RFC), 9 Weather Service Forecast Offices (WSFO), and 20 Weather Service Offices (WSO) located within the Central Region of the National Oceanic and Atmospheric Administration's (NOAA) NWS. The staffs of these forecast and warning offices worked tirelessly to provide high-quality services over a period of several months. Their continuous contributions clearly saved many lives and prevented substantial increases in property damage.

The duration and magnitude of the event placed enormous stress on both humans and the forecast system infrastructure. Given current resources and system limitations, the forecasts and warnings were incredibly good. For example, at the peak of the flood along a stretch of the Mississippi River near Hannibal, Missouri, approximately 50 percent of the estimated 4 million gallons of water per second was flowing outside the "main channel" of the river and behind the levee systems. In spite of these complex hydraulic conditions, the North Central RFC provided forecasts for the city of Hannibal that were sufficiently accurate and timely to allow the U.S. Army Corps of Engineers (COE) and the city of Hannibal to take action to reinforce the major levee system protecting the city. Although numerous anecdotes of major mitigation actions, such as this one, could be presented, there are still substantial opportunities for improvements that will provide significant benefits during future flood events and that will pay even larger dividends to the Nation.

One overriding conclusion reached by the survey team is that the magnitude and historical importance of The Great Flood of 1993 warrants considerable additional research and study to benefit from all lessons to be learned. The total scope of potential lessons learned will pertain not only to ways of improving prediction capabilities but also to water resources planning and assessment, water law, water use policy and regulation, flood mitigation strategies, facility operations, water management decisions, and hydrologic warning and public response. Only those aspects directly related to the quality of hydrometeorological predictions and ensuing user response were considered by the survey team.

FINDING 2.1: The meteorological, climatological, hydrological, and hydraulic conditions that converged to produce The Great Flood of 1993 were unique in many aspects. Initial assessments of the economic impact of The Great Flood of 1993 indicate that losses will range between $15-20 billion. This is the single, greatest flood loss in the Nation's history and rivals Hurricane Andrew in overall losses. The extent of social disruption is beyond measure.	**RECOMMENDATION 2.1:** NOAA should work closely with its many collaborators to encourage further investigations into the various aspects of The Great Flood of 1993. Much is left to be learned. Additional scientific studies should be conducted to provide important insights on how to further minimize losses from future disastrous floods.
FINDING 2.2: There were major benefits, as well as some problems, related to the many uses of NWS flood forecasts. The disaster survey team was unable to assess comprehensively the impact of the hydrologic forecasts and products due to the limited duration of the survey. Because of the large socioeconomic impacts of this historic flood event and the potential mitigating effects of higher-quality hydrologic forecasts, a more detailed post-flood impact analysis would be invaluable.	**RECOMMENDATION 2.2:** NOAA should support a comprehensive, external study to evaluate and quantify the benefits derived from hydrologic forecasts. This study should take maximum advantage of the lessons learned during The Great Flood of 1993.

2.3 ADVANCED HYDROLOGIC PREDICTION SYSTEM

Figure 2-1 illustrates the major components or functions of a river forecast system. The disaster survey team identified ways to improve all components of the current forecast system. Chapter 4 discusses the hydrologic and hydraulic models and procedures employed in the current forecast system.

Users indicated great interest in improving hydrologic prediction to help mitigate the impacts of future floods. The staggering loss of $15-20 billion in The Great Flood of 1993 clearly indicates a need to cut future losses. The key to providing improved river and flood forecasts in the future will depend on establishing and maintaining an Advanced Hydrologic Prediction System (AHPS). The Department of Commerce and NOAA, in partnership with other major cooperators, are committed to the development and implementation of an AHPS to improve services to the Nation. This effort is a key component in the NOAA 1995-2005 Strategic Plan to enhance NOAA's role in environmental prediction. The basic components of an AHPS are illustrated in Figure 2-2.

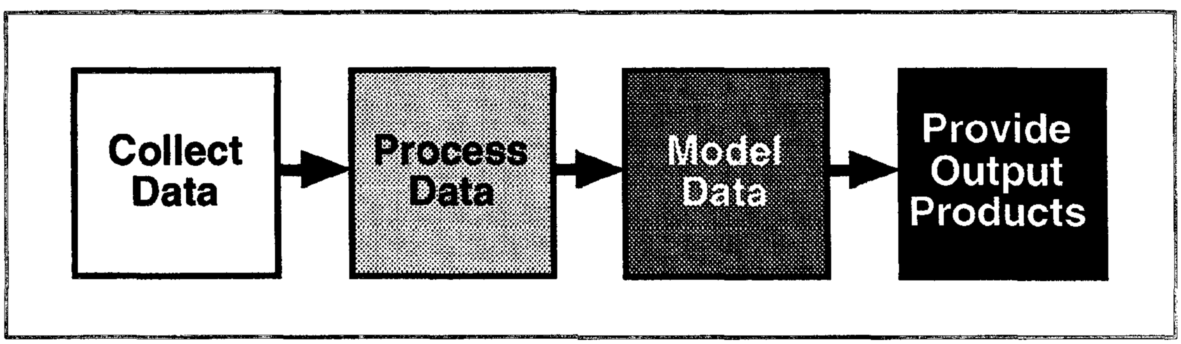


Figure 2-1. *Major functions of a river forecast system.*

2.3.1 NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

Figure 2-2 shows that the first major building block critical to the foundation of an AHPS is the current NWS River Forecast System (NWSRFS), including all of the supporting personnel and service infrastructure. Both the North Central and Missouri Basin RFC staffs expressed concern that sufficient depth of expertise and training be maintained at both NWS Headquarters and the RFCs to support properly the NWSRFS. The NWSRFS consists of software modules totaling several hundred thousand lines of computer code used to execute all functions shown in Figure 2-1. It is a modular software system that allows the addition of more advanced data processing and modeling techniques as they become available. A more detailed description of NWSRFS is given in Chapter 4 (Section 4.3).

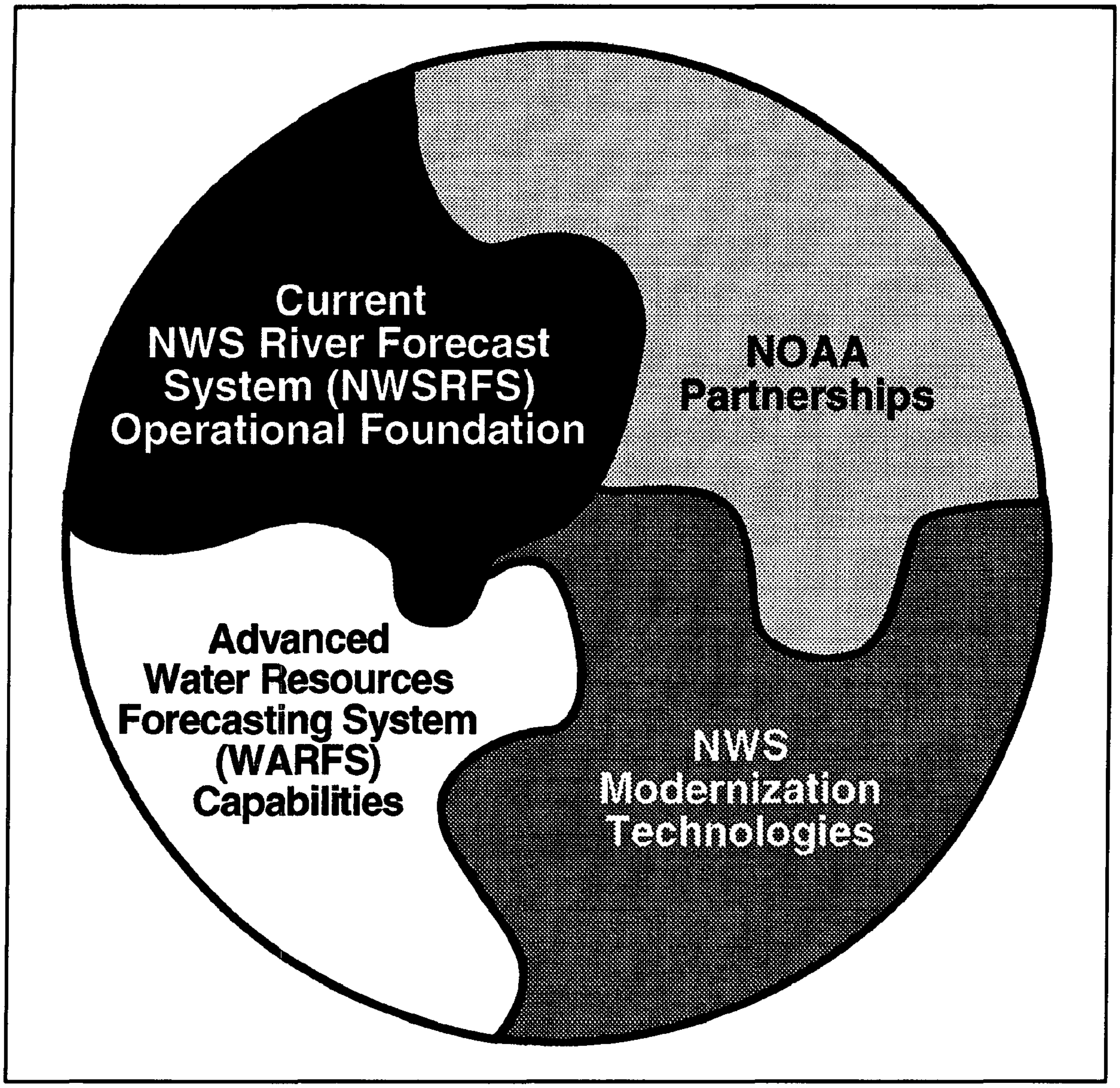


Figure 2-2. *Basic components of an Advanced Hydrologic Prediction System (AHPS).*

A critical component required to improve model development and calibration is the capability to archive routinely the real-time, operational, hydrometeorological data in digital format. This capability does not currently exist at the RFCs, nor at the National Meteorological Center (NMC), for much of the hydrometeorological data needed to support hydrologic research and development.

FINDING 2.3: A large suite of software and hydrologic procedures, especially NWSRFS, is critical to current RFC operations and even more critical to future operations. There is significant concern about maintaining the required depth of expertise and support at both the field and headquarters levels required for this complex system.	**RECOMMENDATION 2.3:** The NWS Office of Hydrology should systematically evaluate the operational readiness of NWSRFS and other software used in hydrologic forecasting.
FINDING 2.4: RFCs do not routinely store river and flood forecast information and products in digital form. Similarly, the NMC does not routinely archive quantitative precipitation forecast products in digital form. These data and forecast products are critical for post-event analyses, research and development, model calibration, extended streamflow prediction and simulation requirements, climatological studies, and forecast verification.	**RECOMMENDATION 2.4:** Routine procedures must be implemented at the NMC and the RFCs, as part of modernized system capabilities, to archive all data and products in digital format that are pertinent to ongoing developmental, operational, and verification programs.

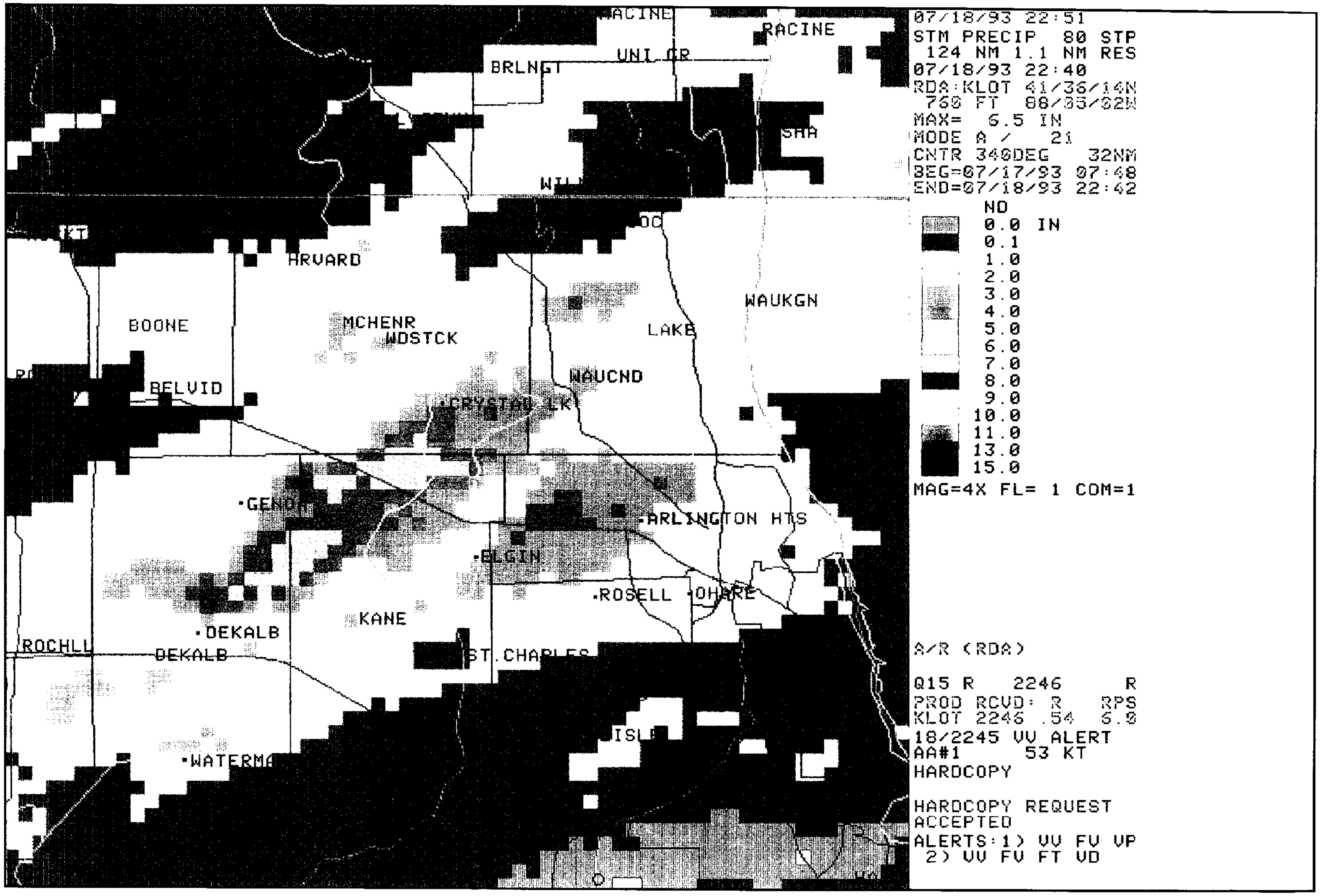


Figure 2-3. *Chicago, Illinois, WSR-88D image showing storm total precipitation ending at 5:42 p.m. CDT (22:42 UTC) on July 18, 1993.*

2.3.2 NATIONAL WEATHER SERVICE MODERNIZATION

A second major building block for the AHPS is the capability provided by the NWS modernization and associated restructuring (MAR). The NWS MAR includes organizational and human resource components needed to take advantage of modernization technologies, principally the Next Generation Weather Radar (NEXRAD) network, the Advanced Weather Interactive Processing System (AWIPS), and the next generation of geostationary environmental satellites. NWS modernization contributes to improved hydrologic prediction through:

1. On-site, powerful, interactive computer processing that supports:
   - a modern, interactive river forecast system; and
   - interactive precipitation analysis using data from radar, satellite, aircraft, and automated surface gages;

2. Rapid, wide-band communications; and

3. More effective use of human resources.

Even in the early stages of the implementation of NWS modernization technologies, it is clear that the payoff in improved forecasts and warnings will be enormous. Several examples were noted by the disaster survey team when Weather Surveillance Radar 1988 Doppler (WSR-88D)--the nomenclature for NEXRAD radars--rainfall estimates were used to provide flash flood warnings. One example is illustrated in Figure 2-3, where the Chicago WSR-88D detected a heavy rainfall area between DeKalb and Crystal Lake, Illinois. The radar display provides an estimate of the storm total ending at 5:42 p.m. CDT on July 18, 1993. Precipitation accumulations exceeded 6.5 inches. These radar observations led to the issuance of a flash flood warning. A greater lead-time, however, could have been given if the flash flood potential (FFP) algorithm had been implemented in the WSR-88D Radar Product Generator. Implementation of the FFP has been under configuration management review for an extended period.

Current RFC computer resources lag the state of the art considerably and impact forecast operations in many ways. One critical example is that AWIPS-type computer resources will be required at RFCs to process and to mosaic the radar rainfall estimates from multiple radars providing coverage of the RFC's area of responsibility. At WSFOs, little or no local hydrologic forecast capability exists now. AWIPS-type computer resources will also be needed at the Weather Forecast Offices (WFO) of the modernized NWS to provide a Hydrometeorological Forecast and Warning subsystem to assist WFO personnel to forecast for small, quick-responding basins.

Critical also to the modernization effort is the professional staffing of personnel trained in both the hydrologic and meteorologic sciences. The disciplines are distinct but interconnected. It is critical that NWS offices be staffed with qualified personnel trained to provide the hydrometeorological support required by the AHPS. The modernized hydrology program provides for Hydrometeorological Analysis and Support positions in the modernized RFCs and for new qualification criteria for hydrometeorologists. Although these new hydrometeorologist criteria have been defined, suitable changes in the personnel, recruitment, qualification, and promotion process have not yet been implemented.

<u>FINDING 2.5:</u> Although only nine WSR-88D radars had been installed for areas covering parts of the flooded states, several instances illustrated the revolutionary impact the WSR-88D will have on flood and flash flood forecasts and warnings. One especially noteworthy example occurred on July 18, 1993, when the Chicago WSR-88D accurately mapped a 4.0- to 6.6-inch rainfall core that led to a warning being issued prior to significant flooding. Greater lead-time could have been provided, however, if the FFP algorithm had been implemented in the WSR-88D Radar Product Generator.	<u>RECOMMENDATION 2.5:</u> Every effort must be made to keep the NWS modernization on schedule and to accelerate its implementation and operational support. It is imperative that the change-management process for the WSR-88D program be streamlined so that it does not take a year, or longer in some cases, to get critical software changes or enhancements implemented--the FFP algorithm being a case in point. Furthermore, AWIPS-type capabilities must be installed at the RFCs to use effectively WSR-88D rainfall estimates for numerical input to hydrologic models.
<u>FINDING 2.6:</u> WSFOs in the affected area have headwater tables for selected basins that are used to provide flash flood guidance. Nonetheless, many offices felt a need for more advanced, local river forecast procedures to produce headwater forecasts systematically or to update RFC forecasts. This was especially critical in situations in small river basins where hydrometeorological conditions changed rapidly.	<u>RECOMMENDATION 2.6:</u> NWS national and regional headquarters, NWS field offices, and the Forecast Systems Laboratory of the Office of Oceanic and Atmospheric Research should accelerate development of the WFO Hydrometeorological Forecast and Warning Subsystem for incorporation into the AWIPS application software suite.

<u>FINDING 2.7:</u> The modernized NWS has a critical need for professional personnel trained in both hydrology and meteorology and has developed qualification criteria for these new hydrometeorologists.	<u>RECOMMENDATION 2.7:</u> NWS and NOAA managers and personnel offices must ensure that personnel, recruitment, qualifications, and promotion processes appropriately reflect requirements for hydrometeorologists.

2.3.3 PARTNERSHIPS WITH COOPERATORS

The third building block critical to the successful implementation of an AHPS is external cooperator support. It is important to continue the high priority of developing and maintaining even closer partnerships with NOAA's many cooperators. This undoubtedly is the most important component of the AHPS as depicted in Figure 2-2, since NOAA's partners at Federal, state, and local levels, as well as in the academic and private sectors, contribute directly and indirectly to many aspects of an effective prediction system. Specifically, closer coordination and cooperation with the COE and the Federal Emergency Management Agency, which clearly had a major role in mitigating and responding to the effects of The Great Flood of 1993, is especially critical.

<u>FINDING 2.8:</u> The effectiveness of the NWS's river forecasting services critically depends on other Federal, state, and local agencies for (1) information used in the forecasting process, (2) the dissemination of forecasts and warnings, and (3) ensuring that the public take actions necessary to prevent loss of life and to mitigate damage.	<u>RECOMMENDATION 2.8:</u> The NWS needs to maintain and strengthen cooperative arrangements with current partners and to seek additional opportunities to work with interested parties to ensure the protection of life and property.

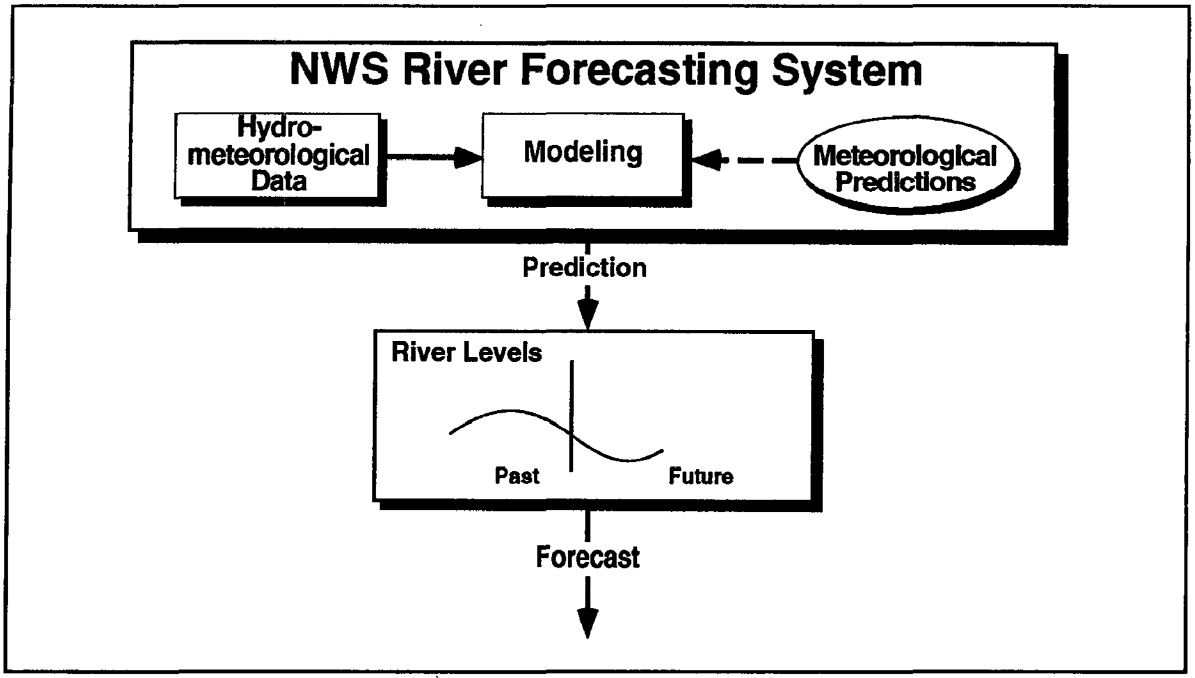


Figure 2-4. *Current NWS River Forecasting System (NWSRFS).*

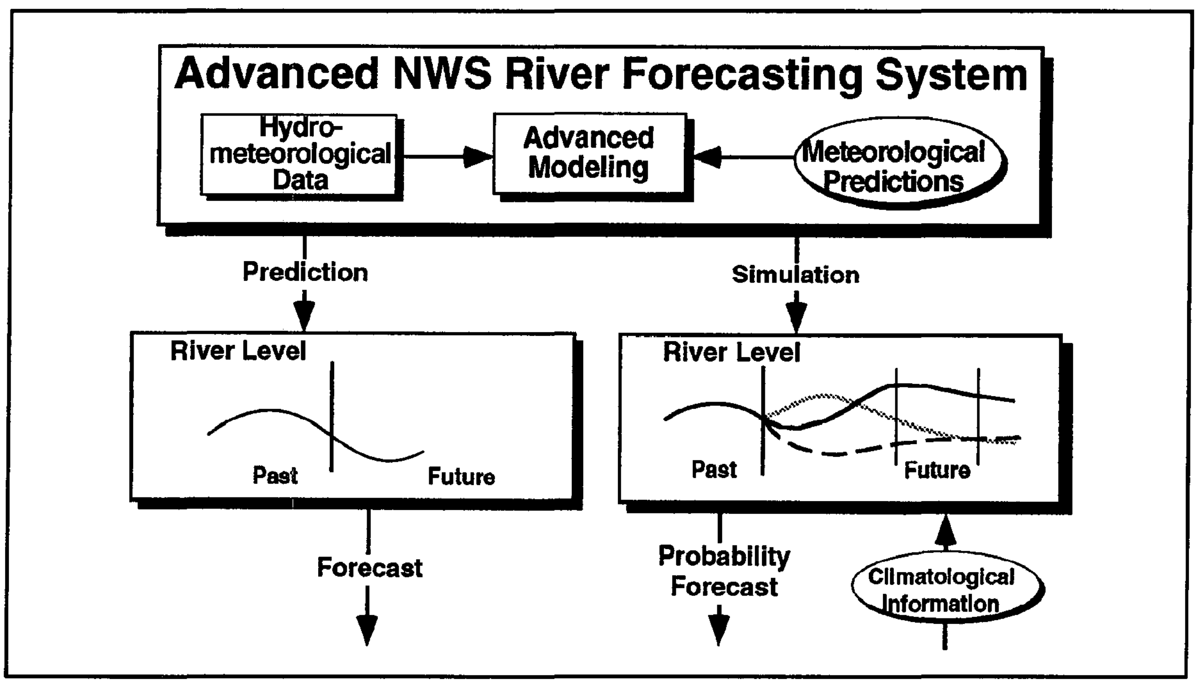


Figure 2-5. *Advanced NWS Water Resources Forecasting System (WARFS).*

2.3.4 WATER RESOURCES FORECAST SYSTEM

The fourth major building block of an AHPS is the capability provided by the Water Resources Forecast System (WARFS). Almost every user visited by the disaster survey team expressed a desire for river forecasts with greater lead-times. Some also wanted forecast ranges, or probabilities of occurrences, to accompany river forecasts that, in some way, consider future precipitation possibilities. WARFS will accommodate these requirements through the use of:

1. Advanced hydrologic and hydraulic models,

2. Integrated data management and analysis techniques,

3. Coupled rainfall and temperature forecasts,

4. Advanced remote sensing and analysis of snow water equivalent, and

5. A consortium of cooperative efforts with NOAA's partners.

A comparison of Figures 2-4 and 2-5 illustrates the major enhancements that WARFS will provide over the current NWSRFS capabilities. The most important changes will be the application of more advanced hydrologic and hydraulic models using improved hydrometeorological data and the capability to incorporate both short-term meteorological predictions and longer-term, climatological information (Figure 2-5). Quantitative precipitation forecasts (QPF) are not being used directly and objectively in Central Region RFC forecast procedures, but an AHPS with integral WARFS components will allow scenarios to be run that can quantify the probabilities of various hydrologic conditions occurring up to several months in the future. This simulation capability is illustrated in the lower right portion of Figure 2-5.

Figure 2-6 schematically depicts an integrated, operational concept of many of the components of an AHPS including WARFS. Shown in Figure 2-6 are data flowing into an RFC from multiple WSR-88Ds located at WFOs, satellites, aircraft, local flood warning systems, data collection platforms, automated surface observing systems, and cooperative observers. Also shown are QPFs flowing into an RFC from multiple WFOs and from the NMC; other graphical and gridded products also will be provided by the WFOs, the NMC, and the National Operational Hydrologic Remote Sensing Center. These vast amounts of data and information will be processed and managed by AWIPS. Advanced models and analyses will be executed interactively on AWIPS. A whole new generation of products will be produced for use in a broad array of applications, including many that will directly impact major water management decisions for the Nation. WARFS has been designed precisely to provide predictions that will give water managers information critical for more effective decisions that mitigate the effects of floods or droughts.

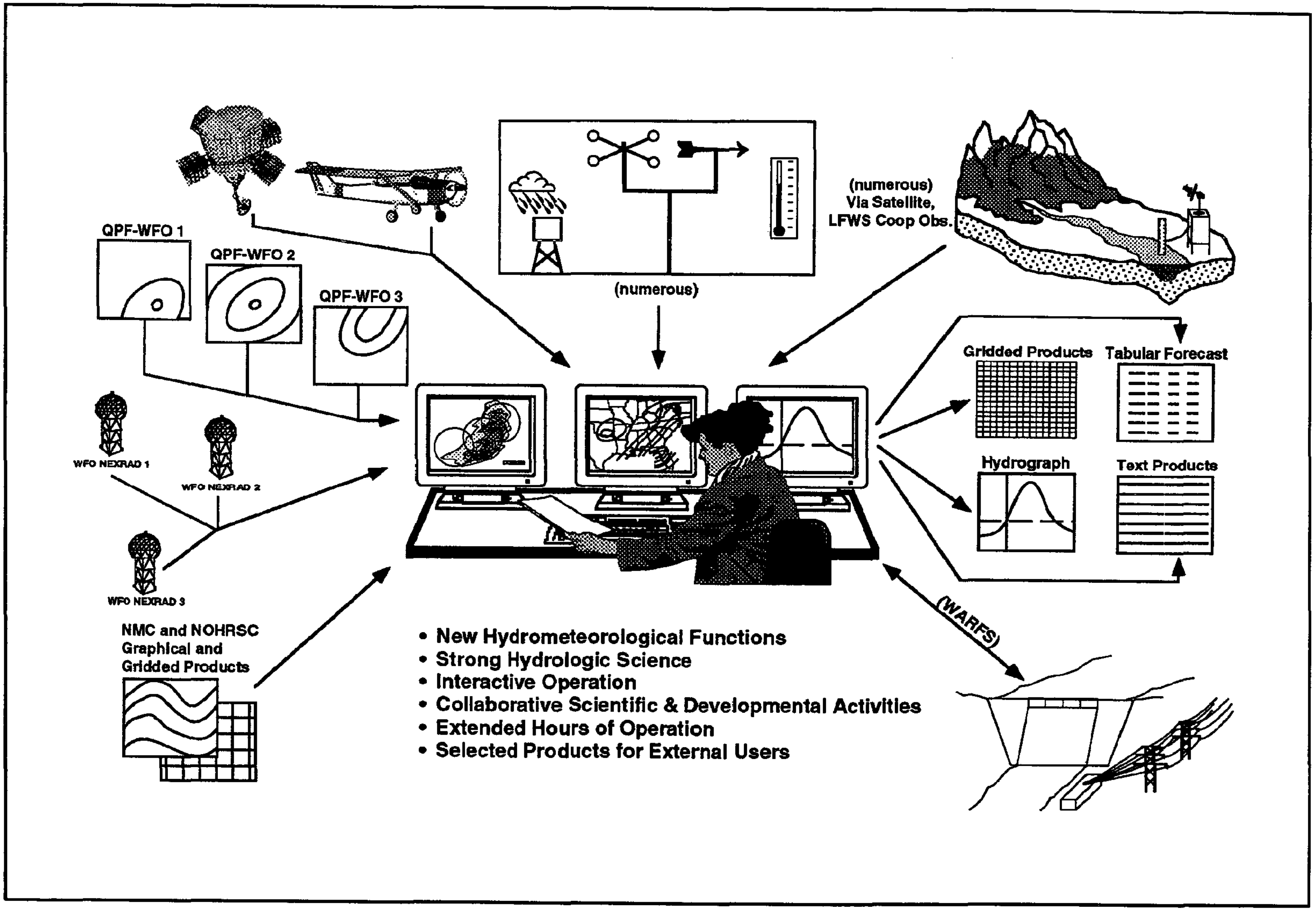


Figure 2-6. *Hydrometeorological operations of a modernized NWS River Forecast Center utilizing AHPS components, including WARFS.*

Figure 2-7 compares the type of forecast that could have been produced at St. Louis with an AHPS, including integral WARFS components, to the type of forecast that was made with current capabilities. The current basis for river predictions is only the first portion of the forecast hydrograph shown as the blue line in Figure 2-7. Especially important is the added lead-time and the quantification of forecast uncertainty provided by the advanced prediction system. Figure 2-8 contrasts the accuracy, lead-time, and resolution of current forecast services with those that could be achieved with an AHPS that includes integrated WARFS components.

<u>**FINDING 2.9:**</u> Currently, RFCs typically issue stage forecasts for only 1, 2, and 3 days into the future at most forecast points and crest forecasts out to about 1 week for a few selected forecast points. Federal, state, and local groups indicated a need for increased lead-times for hydrologic forecasts. Many expressed the need for a range of forecast stages with associated probabilities of occurrence.	<u>**RECOMMENDATION 2.9:**</u> The Federal Government should press forward with implementation of WARFS which will provide the required capabilities.
<u>**FINDING 2.10:**</u> QPFs are not being used directly, objectively, and systematically in hydrologic modeling in Central Region RFCs. In addition, not all WSFOs have appropriate software and computer equipment to issue QPF forecasts for the RFCs. Many users understand that QPF products have inherent uncertainties. Nonetheless, many expressed a need for probabilistic river forecasts that incorporate QPFs.	<u>**RECOMMENDATION 2.10:**</u> If Recommendations 2.6 and 2.9 are implemented, they will also satisfy the requirements to include QPF information in hydrologic forecasts. The NWS should continue to support scientific efforts aimed at producing probabilistic QPFs at WSFOs and WSOs through support of training and research initiatives.

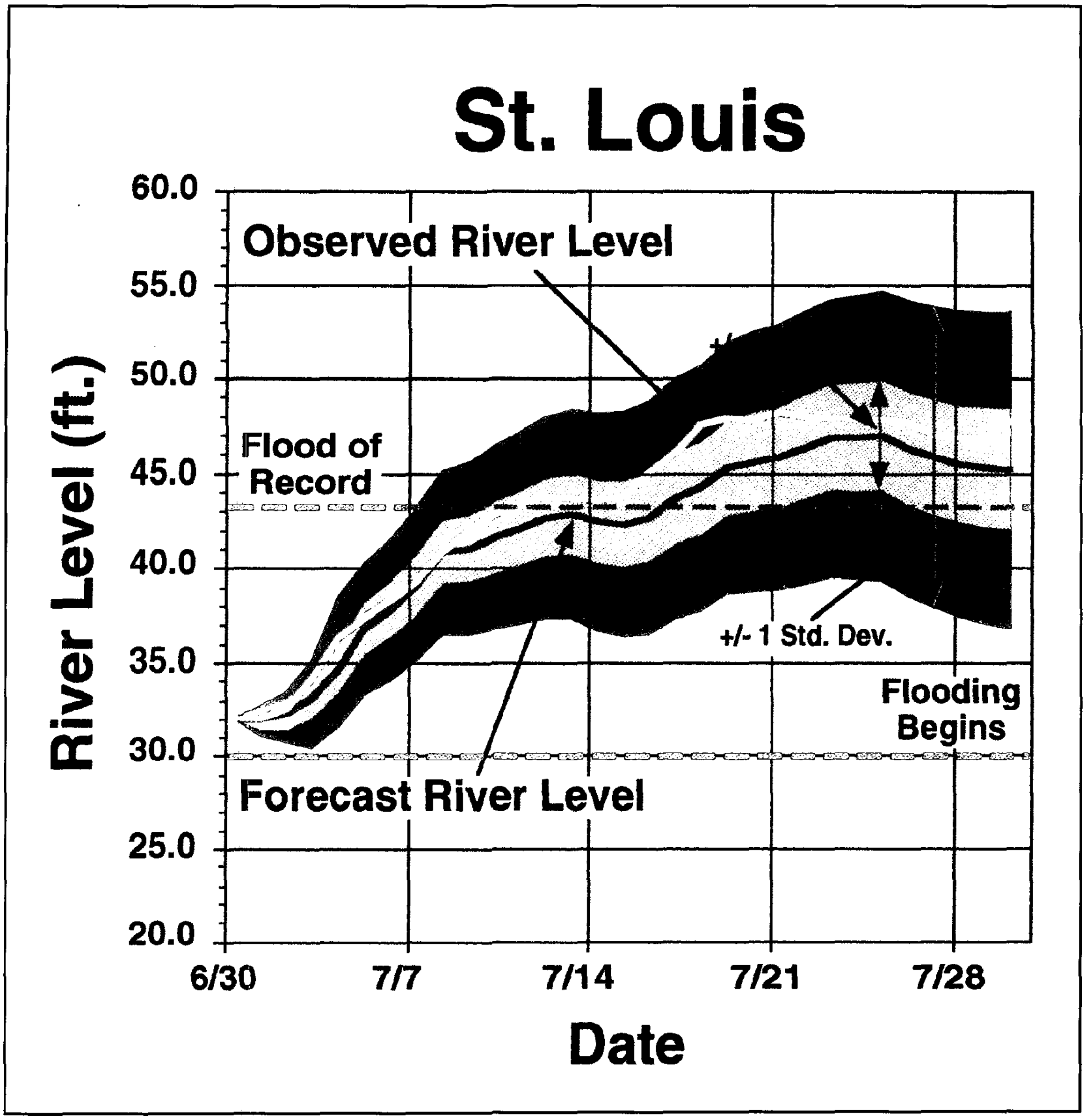


Figure 2-7. *Comparison of observed stage (yellow line) at St. Louis, Missouri, during The Great Flood of 1993 with hypothetical forecast made on June 30 (blue line), using AHPS, including WARFS. Varying confidence intervals around the hypothetical forecast are shown by pink shading (one-half standard deviation above and below the forecast) and green shading (one standard deviation above and below the forecast).*

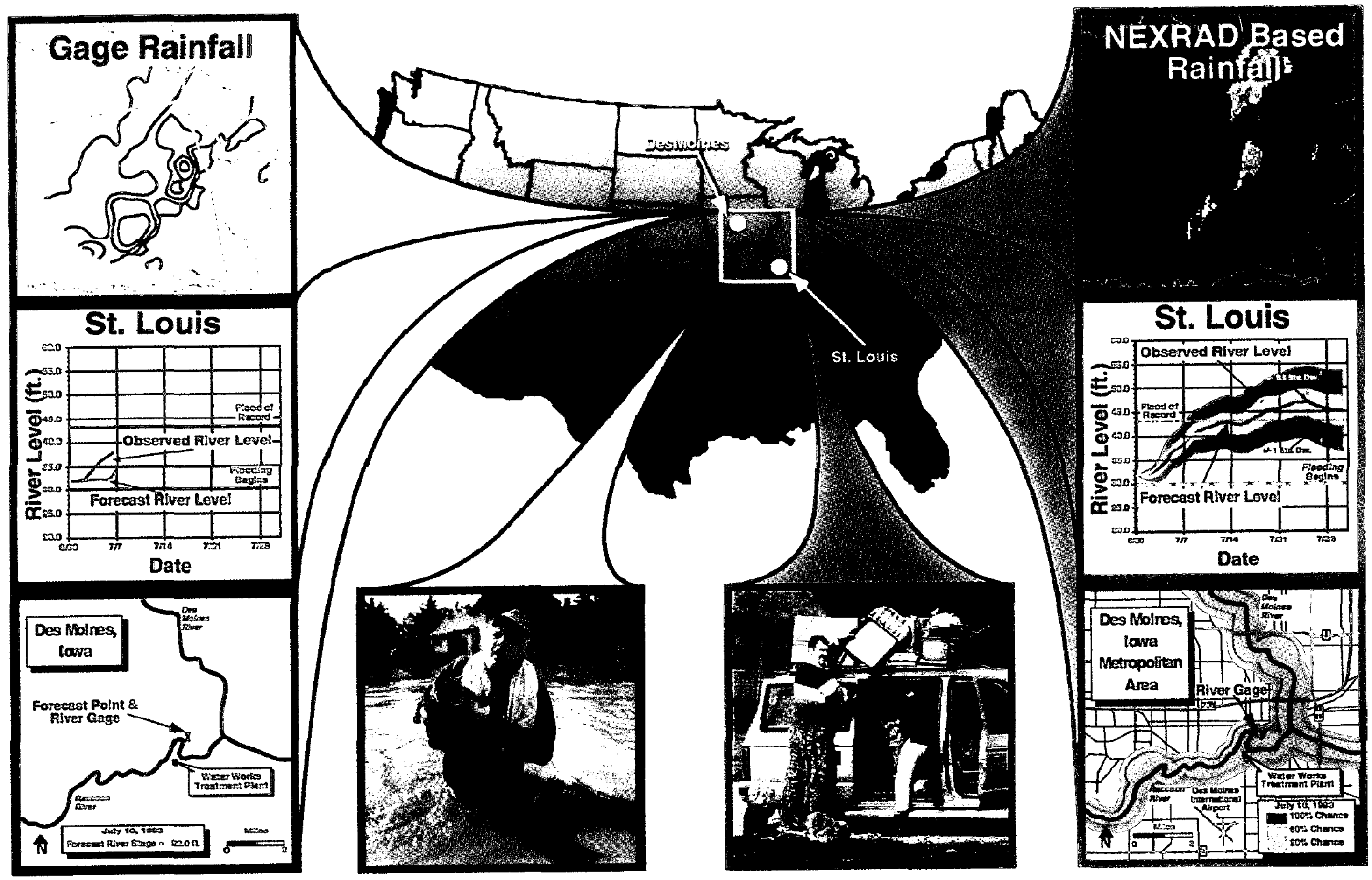


Figure 2-8. *Contrast between current NWSRFS (left side of diagram) and modernized NWS AHPS with integral WARFS components (right side of diagram).*

2.4 NEAR-TERM HYDROLOGIC OUTLOOK AND NEEDS

Finally, it is necessary to take all appropriate actions to prepare for the high potential of additional flooding in the Upper Midwest during the spring of 1994. Above-normal soil moisture conditions over large regions of the Upper Midwest and fall rains coupled with winter snow accumulation increase the probability of potential spring flooding in 1994.

<u>FINDING 2.11:</u> The extensive flooding of 1993 has created large regions with above-normal soil moisture conditions across the Upper Midwest. Consequently, fall rains and spring snowmelt in 1994 may substantially elevate the potential for flooding. There is a need for immediate and extended assessments of flood potential persisting through at least the spring of 1994. Special hydroclimatological assessments done monthly would be valuable.	<u>RECOMMENDATION 2.11:</u> The NWS Office of Hydrology and the Central Region should provide early and ongoing assessments of potential spring flooding in 1994 in the areas affected by The Great Flood of 1993. This effort should draw on early experiences from the NWS modernization and pilot WARFS activities wherever possible. Additionally, information and data from the Midwest Climate Center and NMC's Climate Analysis Center should be used to support an ongoing assessment of soil moisture conditions and potential future flooding across the Upper Midwest. Moreover, the NWS should support an enhanced airborne soil moisture data collection program during the late fall of 1993 and a comprehensive airborne snow water equivalent data collection program during the winter of 1993-94 over the region affected by The Great Flood of 1993.

CHAPTER 3

HYDROMETEOROLOGICAL SETTING

3.1 INTRODUCTION

Flood stage (i.e., the water level at which a river goes into flood) was exceeded at approximately 500 forecast points, and record flooding occurred at 95 forecast points throughout the nine-state region. Some forecast points remained above flood stage for as long as 5 straight months. As shown in Figure 3-1, St. Louis experienced river stages that exceeded the previous flood of record for more than 3 full weeks!

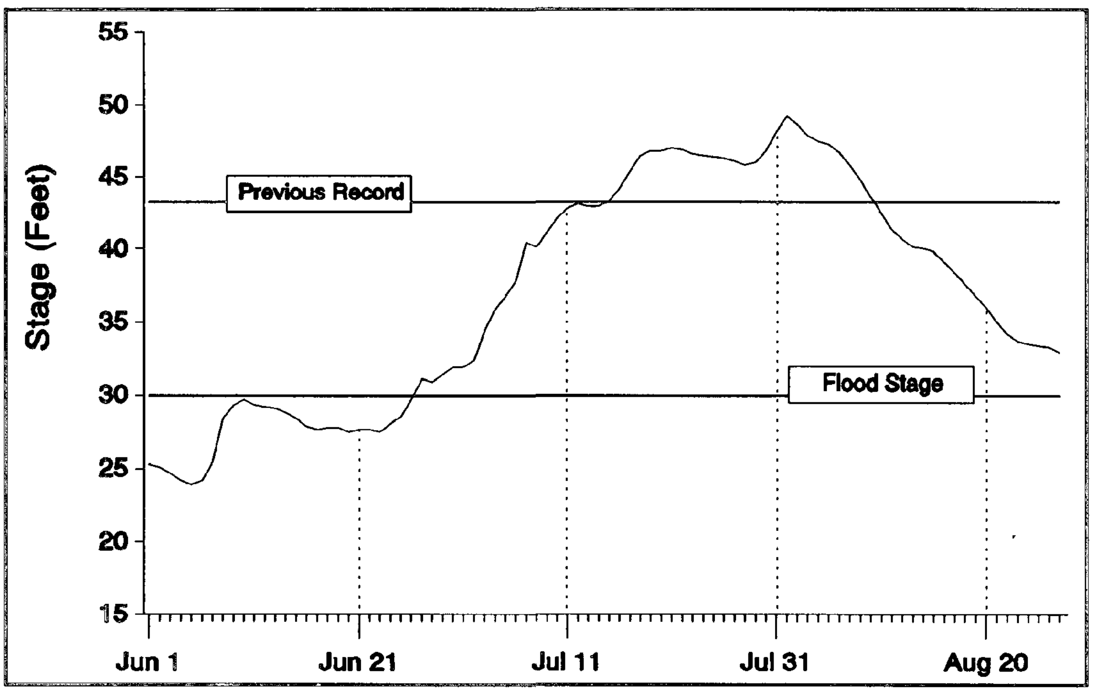


Figure 3-1. *Hydrograph at St. Louis, Missouri. (A hydrograph shows the changes of river stage with the passage of time.)*

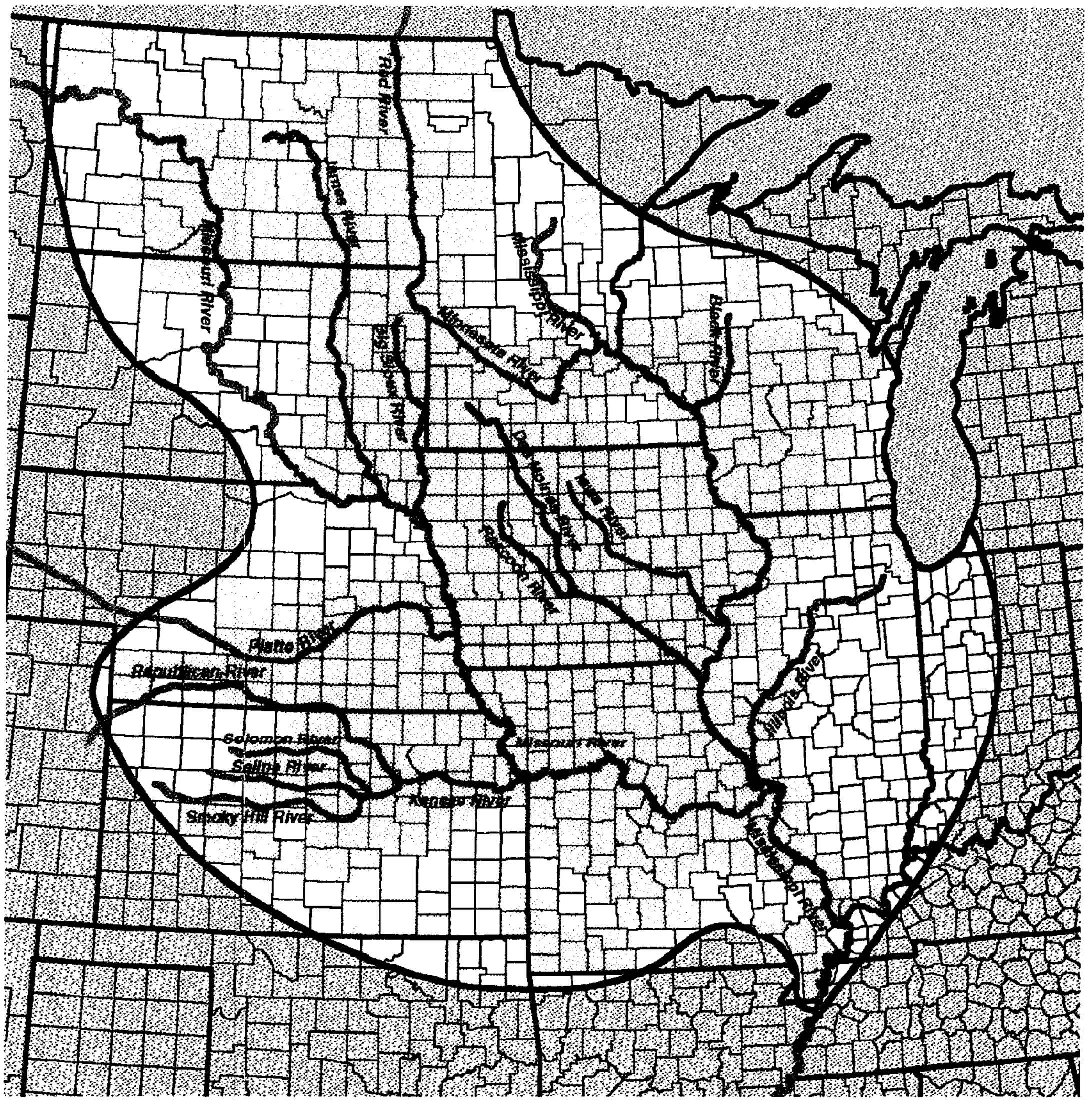


Figure 3-2. *Flood-affected counties which received Federal disaster assistance.*

The flood event was exceptional due to the combination of several factors:

1. The antecedent hydrometeorology: the scene was set for flooding across the flood-impacted area long before major flooding actually developed.

2. The meteorology: the meteorological pattern that caused the excessive rainfall over the region from mid-June into August 1993 was uncommonly persistent.

3. The magnitude of the flooding: the areal extent of the flooding was unusually large.

4. The severity of the flooding: major to record flooding occurred along dozens of rivers, including portions of the main stems of both the Mississippi and Missouri Rivers.

5. The season of the flooding: major flood events in the upper Mississippi River basin typically occur in spring while this occurred throughout the summer.

6. The duration of the flooding: most significant floods last on the order of days-to-weeks, while this flood lasted on the order of weeks-to-months.

7. The damage: preliminary estimates establish this as the costliest flood event in United States history.

All or parts of nine states were declared Federal disaster areas: North Dakota, South Dakota, Minnesota, Wisconsin, Nebraska, Iowa, Illinois, Kansas, and Missouri. Within these nine states, some 500 counties received some form of Federal assistance (see Figure 3-2).

3.2 METEOROLOGICAL ANALYSIS

The flood had its origins in an extended wet period starting 9-10 months prior to the onset of major flooding. This wet period moistened soils to near saturation and raised many stream levels to bankfull or flood levels. This set the stage for rapid runoff and record flooding that followed excessive June and July rainfall. The precipitation was the direct result of major, global-scale circulation anomalies which can be attributed to significant climate variations (see Section 3.2.4).

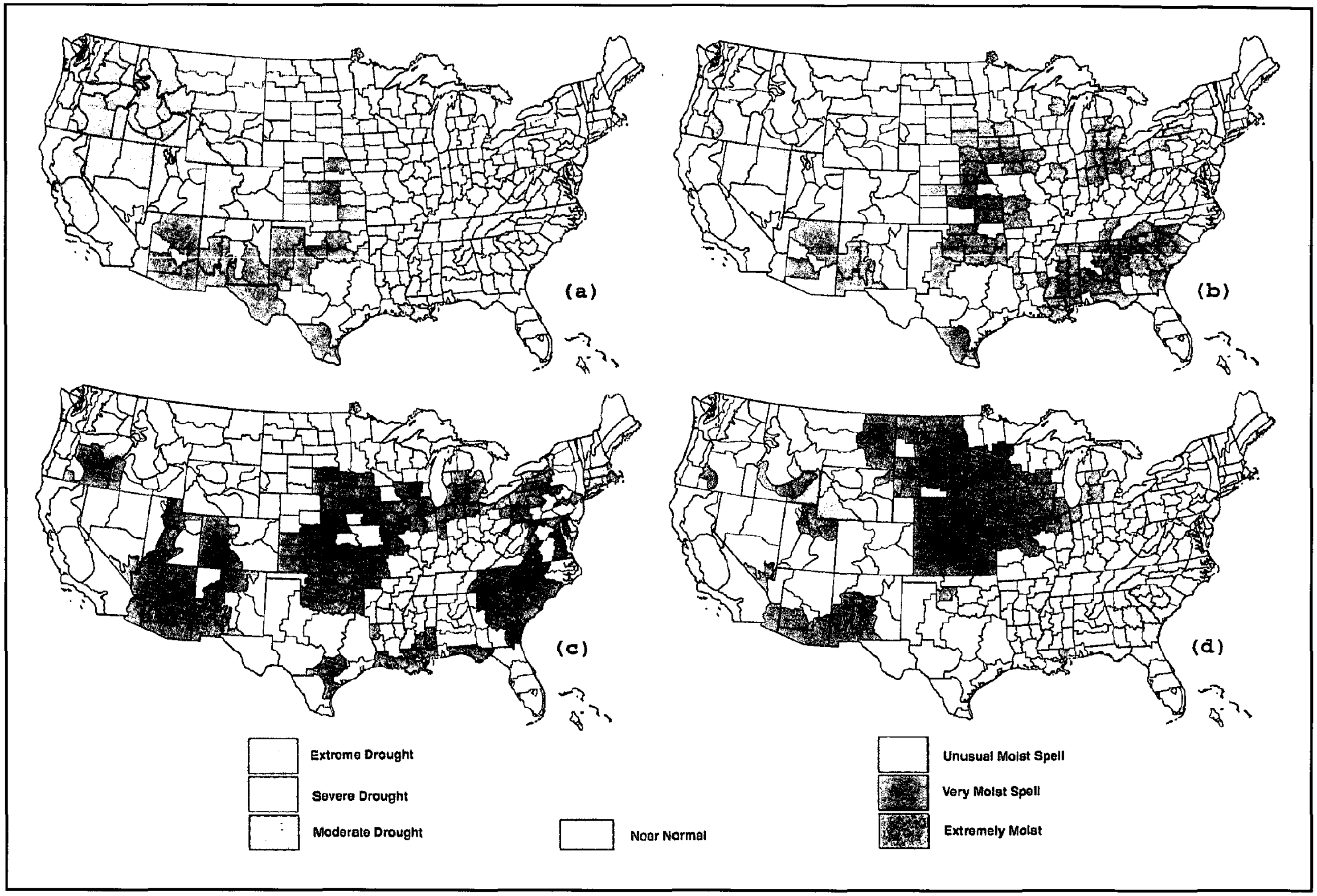


Figure 3-3. *Selected Palmer (Long-Term) Drought Severity Index maps for the weeks ending: (a) August 15, 1992, (b) November 28, 1992, (c) March 27, 1993, and (d) August 28, 1993. Note the gradual increase with time in unusually moist soil conditions across the nation's midsection.*

3.2.1 ANTECEDENT CONDITIONS

Soil moisture conditions, as measured by the long-term Palmer Drought Index (PDI), for selected times over the preceding year are shown in Figure 3-3. In August 1992, wet soil conditions began to appear in the central Great Plains (Figure 3-3(a)), then increased dramatically by late 1992 (Figure 3-3(b)), encompassing portions of the central, eastern, and southeastern United States. As shown in Figure 3-4, July, September, and especially November 1992 were much wetter than normal over the upper Mississippi River basin; winter precipitation was near normal.

By late March 1993, extremely moist conditions (PDI > 4) covered much of Kansas, South Dakota, Iowa, eastern Nebraska, southern Minnesota and Wisconsin, and northern Illinois as a result of the combination of the wet fall and spring snowmelt (Figure 3-3(c)). This was followed by above-normal precipitation over the upper Mississippi River basin during April and May (Figure 3-4). Consequently, even before the onset of heavy summer rains, most of the Upper Midwest had saturated soil and well above-normal streamflows.

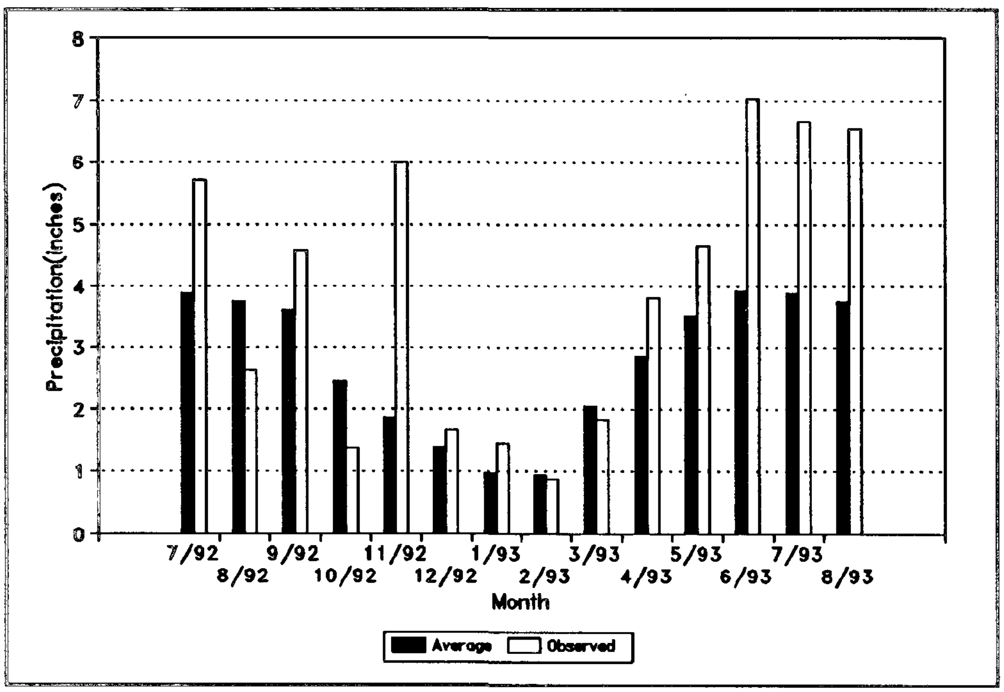


Figure 3-4. *Comparison of average and observed monthly precipitation totals for the upper Mississippi River basin.*

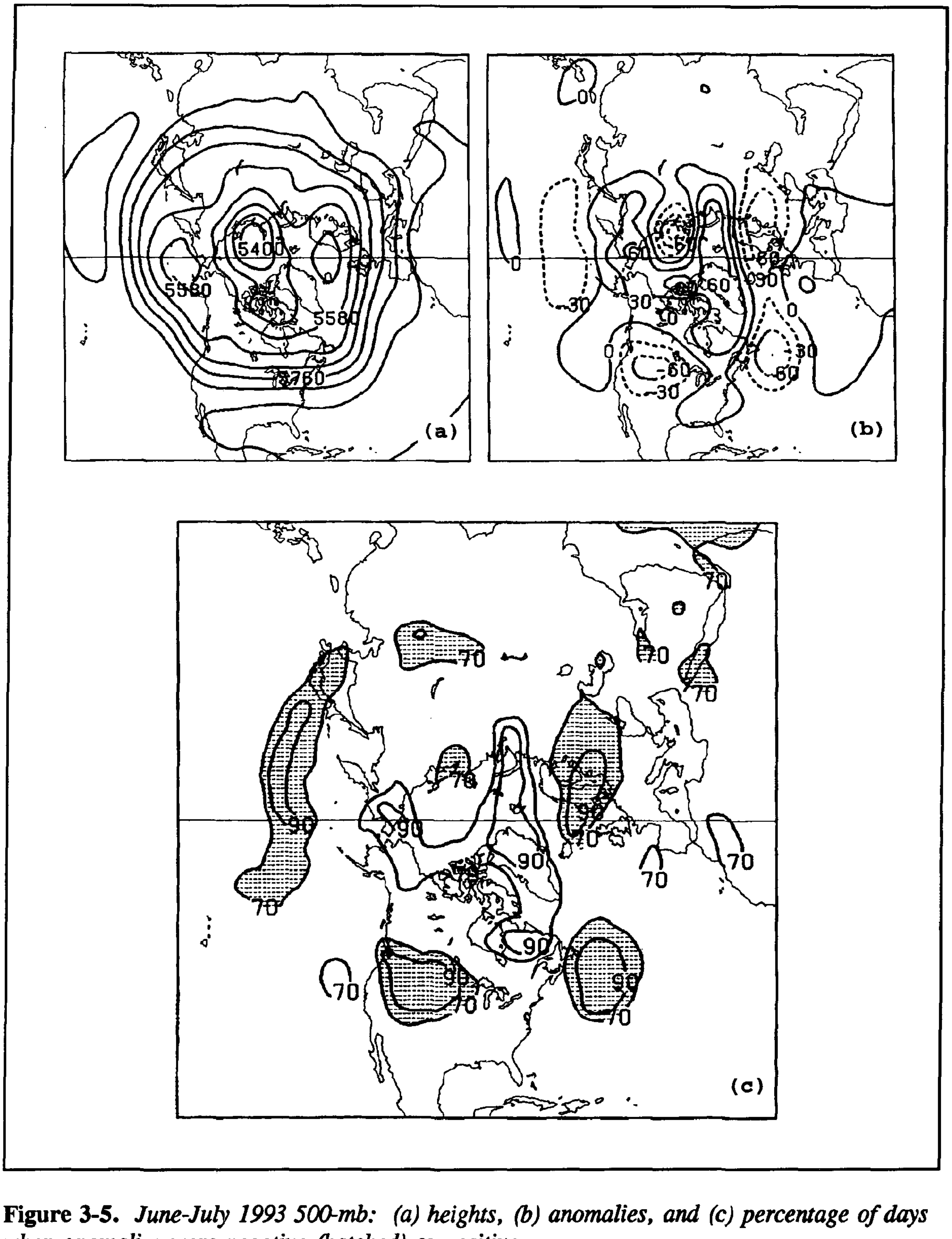


Figure 3-5. *June-July 1993 500-mb: (a) heights, (b) anomalies, and (c) percentage of days when anomalies were negative (hatched) or positive.*

3.2.2 CIRCULATION PATTERNS DURING THE GREAT FLOOD OF 1993

A highly anomalous and persistent atmospheric pattern of excessive rainfall occurred across much of the upper Mississippi River valley and the northern and central Great Plains during June, July, and the first half of August 1993, generating devastating record flooding along the upper Mississippi and lower Missouri Rivers and many of their tributaries. Much of the major river flooding originated from several synoptic-scale, copious rainfall events during mid-June through late July.

This large-scale and repetitive rainfall pattern was just one of many anomalous weather features that affected not only most of the United States but much of the Northern Hemisphere. Elsewhere in the country during June and July, warmer-than-normal conditions persisted throughout Alaska, cooler and wetter-than-usual conditions dominated the Pacific Northwest and northern Great Plains states, and hot and dry weather plagued much of the southeastern and eastern United States. These weather patterns were all related to a highly anomalous circulation that covered much of the Northern Hemisphere, as evidenced by the mean June to July 1993 500-mb height and anomaly field (Figure 3-5), with particular emphasis on the central North Pacific, the United States, the North Atlantic, and Europe.

Climatologically, a low-pressure trough is located near the Gulf of Alaska during the summer months. In April 1993, below-normal sea-level pressures were established in the central and western North Pacific Ocean. This pressure anomaly pattern persisted through June. During June and July 1993, the mean position of the Pacific low-pressure trough moved west to the international dateline. Below-normal sea-level pressures also covered the western United States and much of the North Atlantic from Newfoundland to Scandinavia. Corresponding shifts occurred in the mean position of the jet stream.

By the summer of 1993, the mean position of the jet stream had become firmly established over the northern portion of the Mississippi River basin with a southwest-northeast orientation. To the northwest lay a deep trough of low pressure, while an unusually strong, clockwise circulation lay over the eastern United States. Hot and dry conditions were characteristic of the surface conditions beneath the ridge. The quasi-stationary jet stream aloft was associated with a stationary surface front that allowed frequent and nearly continuous overrunning of the cooler air to the north by the moisture-laden air from the south (Figure 3-6(a)). The front also served as a preferred location for unusually strong and frequent cyclones, spawned by the combination of the unseasonably vigorous jet stream overhead (Figure 3-7) and the relatively strong frontal boundary at the surface.

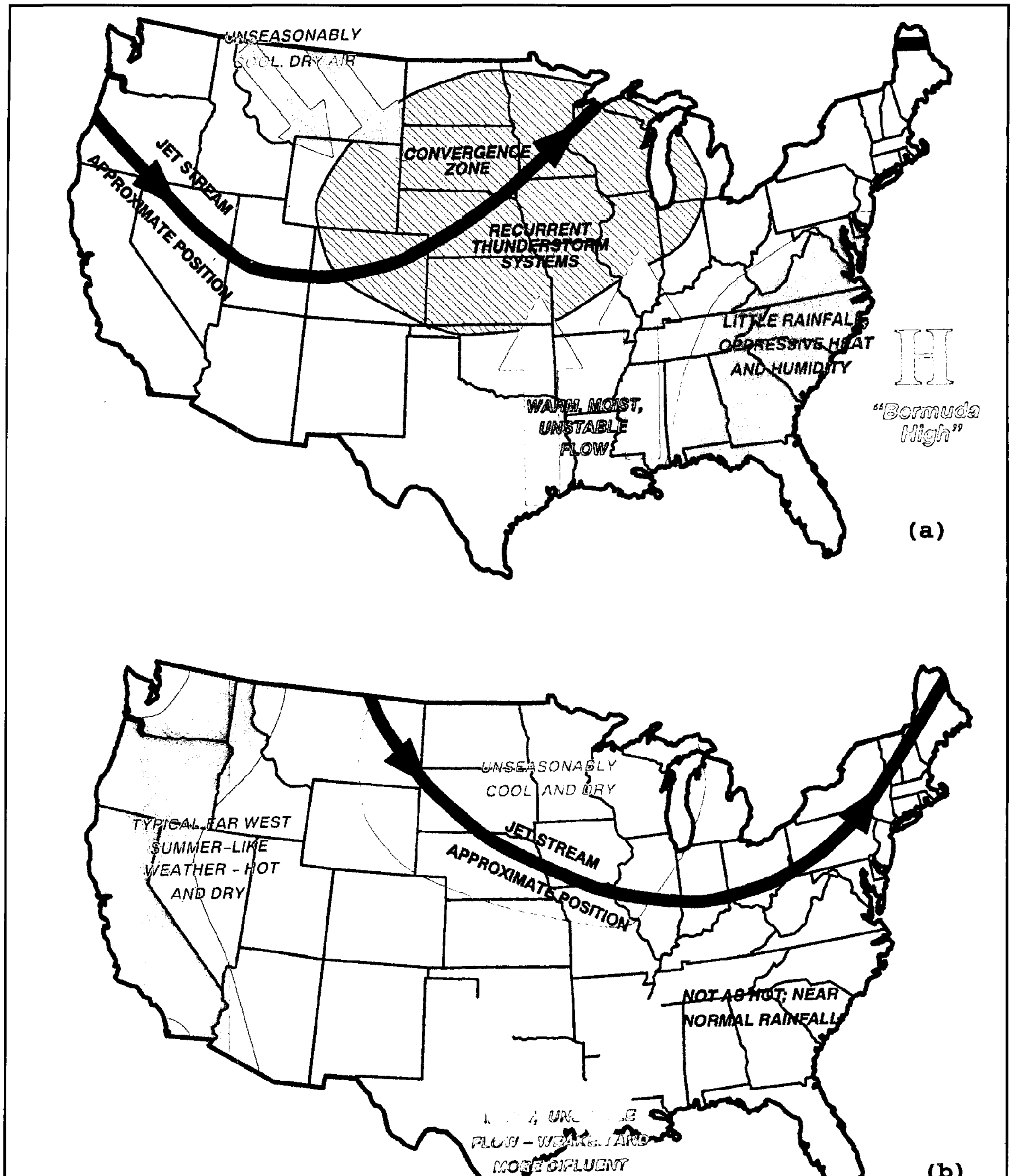


Figure 3-6. *Dominant weather pattern for the periods: (a) June-July 1993 and (b) early August 1993. Note the changes between (a) and (b), particularly across the central United States.*

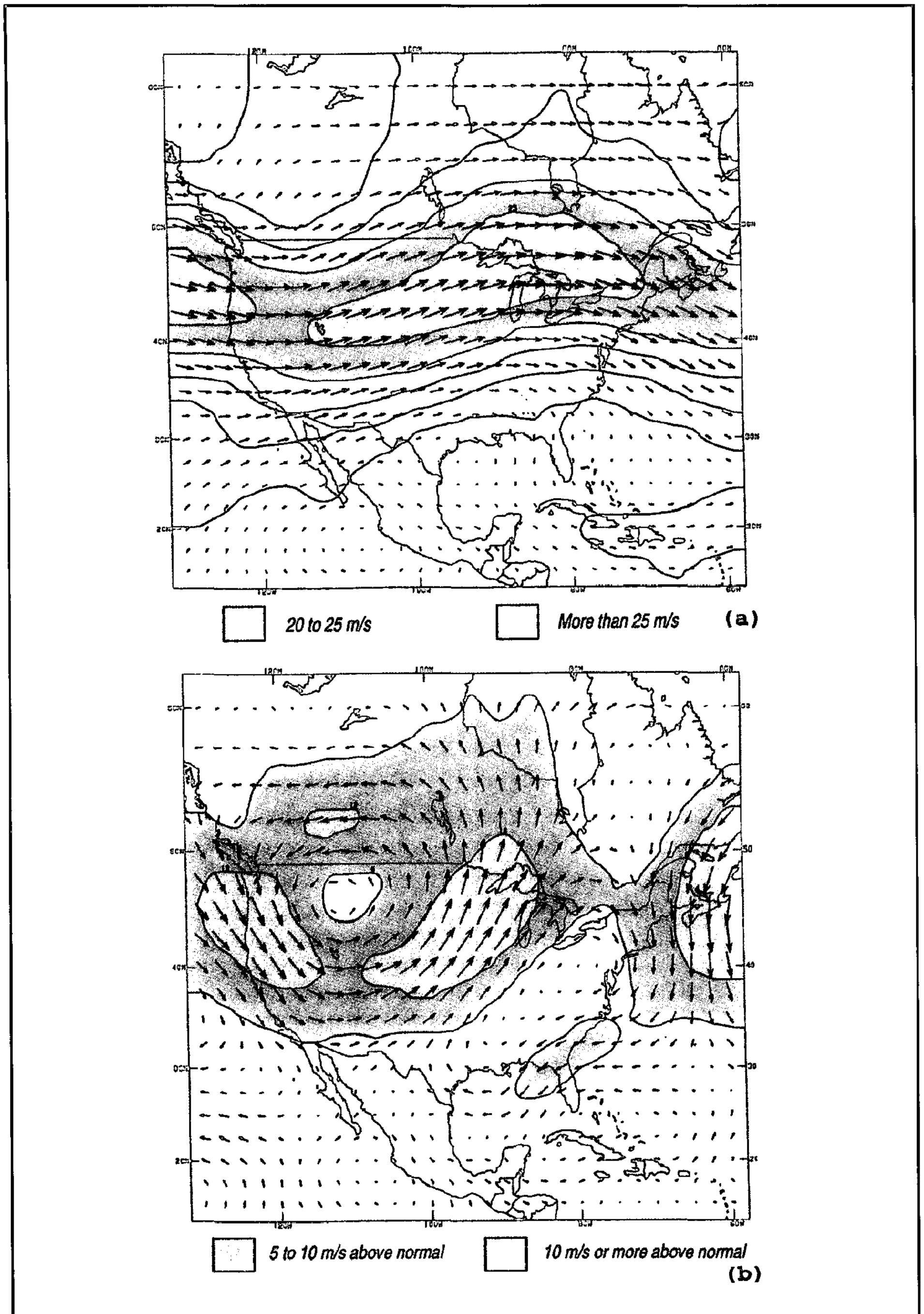


Figure 3-7. *Mean 250-mb flow (approximately 6.5 miles aloft) for the period June 5-July 19, 1993, of: (a) vector wind and (b) departure from normal (base period 1979-1988). Arrows represent the direction and relative strength of the wind or anomaly.*

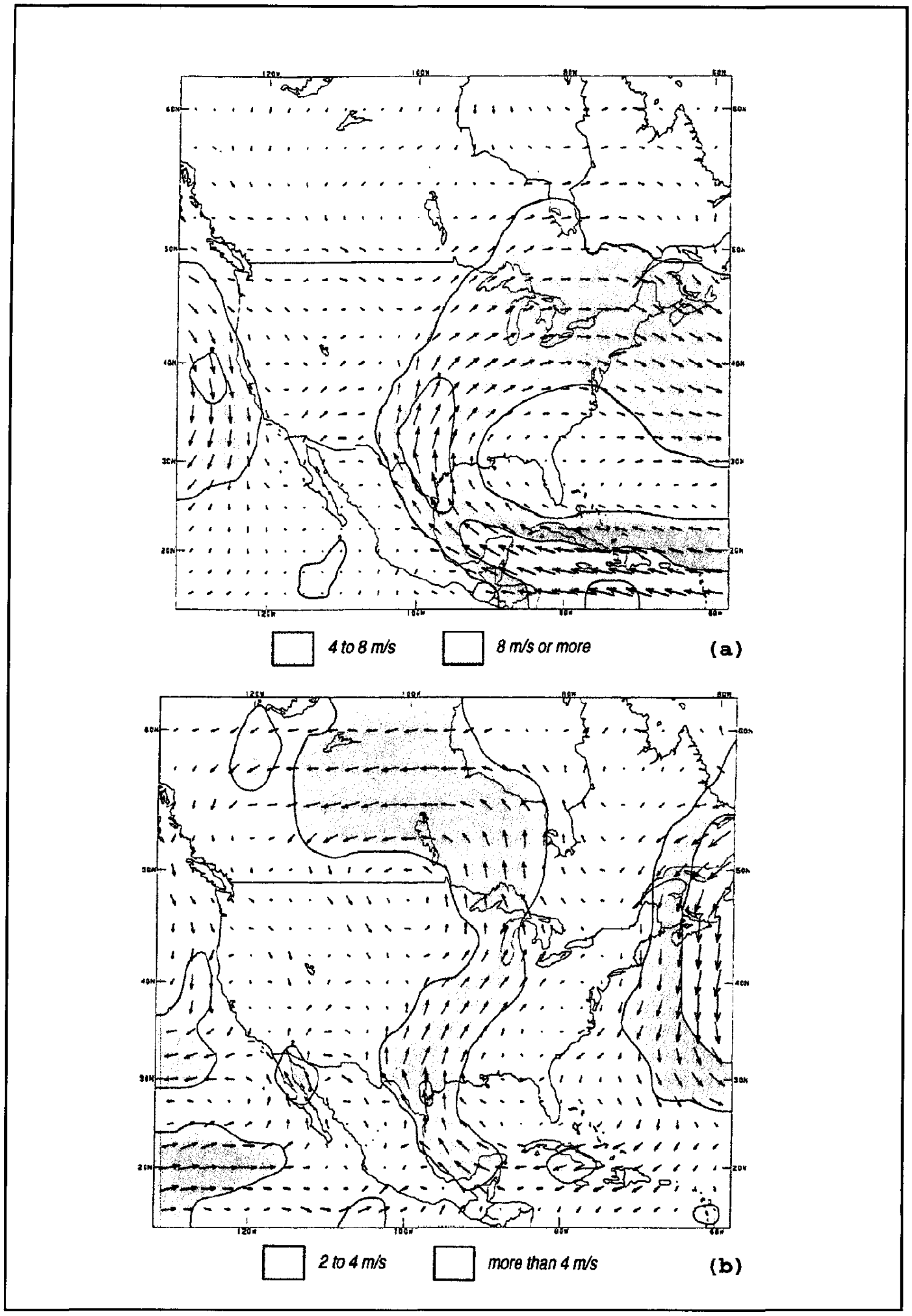


Figure 3-8. *Mean 850-mb flow (approximately 1 mile aloft) for the period June 5-July 19, 1993, of: (a) vector wind and (b) departure from normal (base period 1979-1983). Arrows represent the direction and relative strength of the wind or anomaly.*

North-south transport of moisture was enhanced by strong low-level advection brought about by the unusually large contrast between the trough of low pressure over the northwestern section of the Nation and the ridge of high pressure over the Southeast. Much of this low-level moisture originated in the subtropics in the vicinity of the warm Caribbean Sea waters (Figure 3-8). The increased moisture transport and the presence of the front supported production of widespread areas of prolonged and excessive precipitation throughout large portions of the north-central United States.

Finally, by late July and early August, a change in the upper air circulation pattern brought drier conditions to the Midwest as the trough shifted eastward, simultaneously increasing rainfall and decreasing temperatures in the East while warmer weather returned to the Pacific Northwest (Figure 3-6(b)). Unfortunately, locally heavy thunderstorms generated some additional flooding problems in parts of the soaked Midwest during mid-August; however, these rains were associated with more typical summertime convection caused by frontal passages that were enhanced by strong advection of southwestern monsoonal moisture.

3.2.3 RAINFALL PATTERNS DURING THE GREAT FLOOD OF 1993

During the summer (June-August 1993), rainfall totals surpassed 12 inches across the eastern Dakotas, southern Minnesota, eastern Nebraska, and most of Wisconsin, Kansas, Iowa, Missouri, Illinois, and Indiana. More than 24 inches of rain fell on central and northeastern Kansas, northern and central Missouri, most of Iowa, southern Minnesota, and southeastern Nebraska, with up to 38.4 inches in east-central Iowa (Figure 3-9). These amounts were approximately 200-350 percent of normal from the northern plains southeastward into the central Corn Belt. Since the start of the growing season (April 1), precipitation amounts through August 31 were even more impressive (Figure 3-10): totals approached 48 inches in east-central Iowa, easily surpassing the area's normal annual precipitation of 30-36 inches.

There was considerable variation, both in timing and distribution of heavy rainfall throughout the event. Figure 3-11 shows rainfall and the amount in excess of normal for four selected cities (Sioux Falls, South Dakota; LaCrosse, Wisconsin; Salina, Kansas; and Des Moines, Iowa). By early May, all four cities started to experience excess precipitation; in each area, the surplus increased as the summer wore on. For almost a month, starting in late June, the precipitation excess at Salina, Kansas, was especially dramatic (see Figure 3-11).

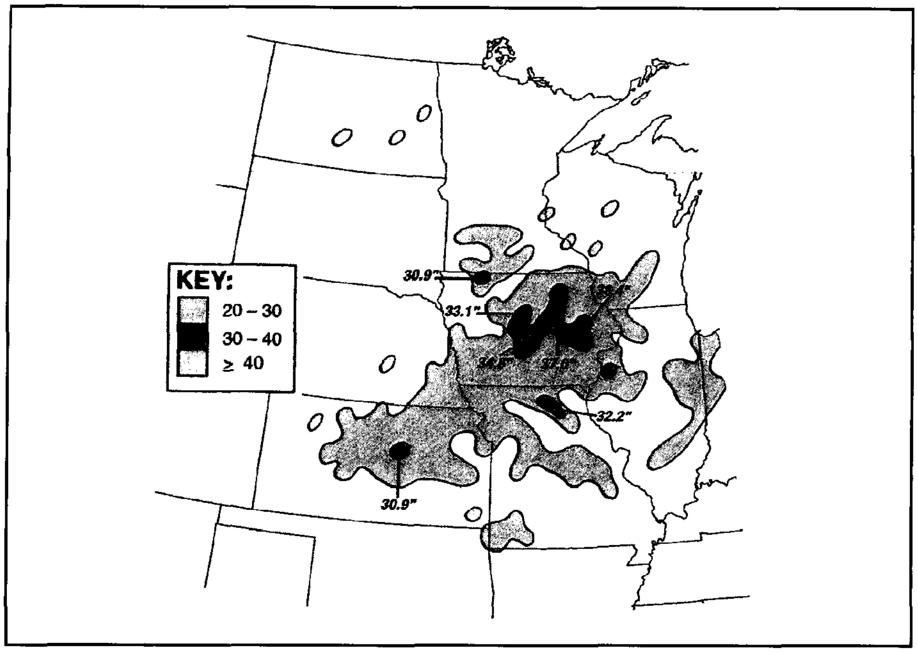


Figure 3-9. *Total precipitation (inches) across the Midwest for the period June 1-August 31, 1993.*

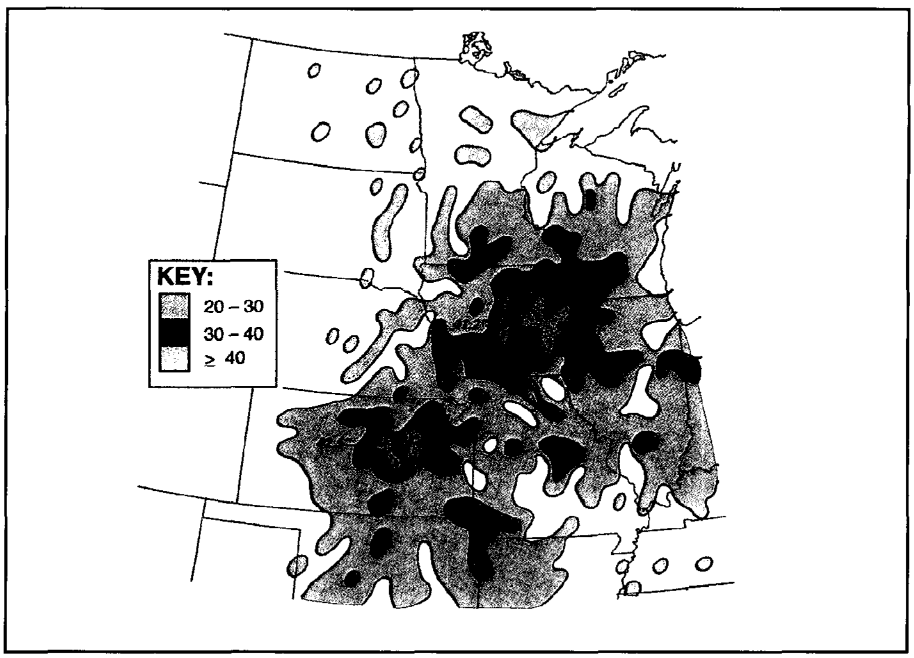


Figure 3-10. *Total precipitation (inches) across the Midwest for the period April 1-August 31, 1993.*

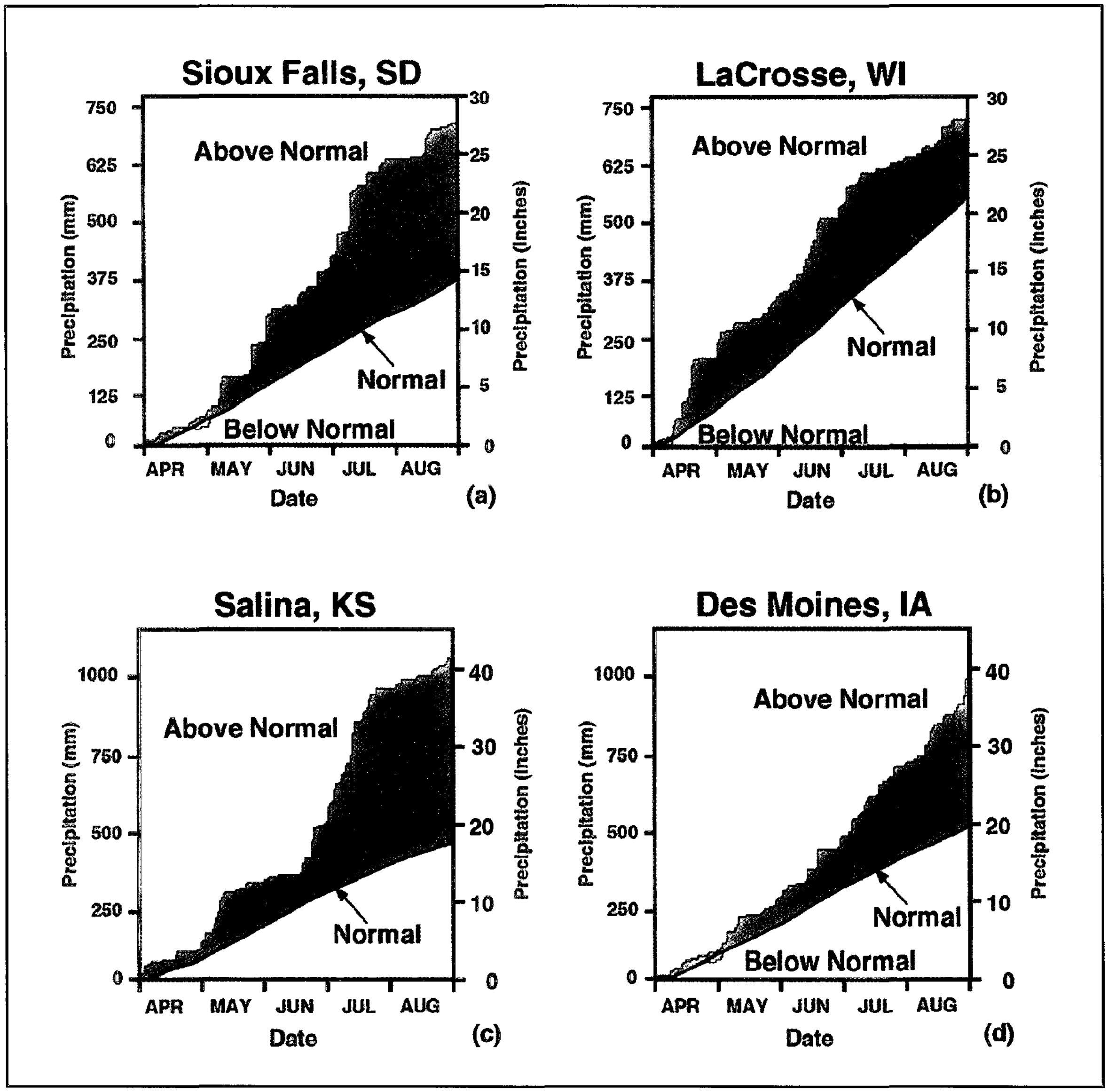


Figure 3-11. *Cumulative precipitation (inches) for the period April 1-August 31, 1993, compared to normal for: (a) Sioux Falls, SD, (b) LaCrosse, WI, (c) Salina, KS, and (d) Des Moines, IA.*

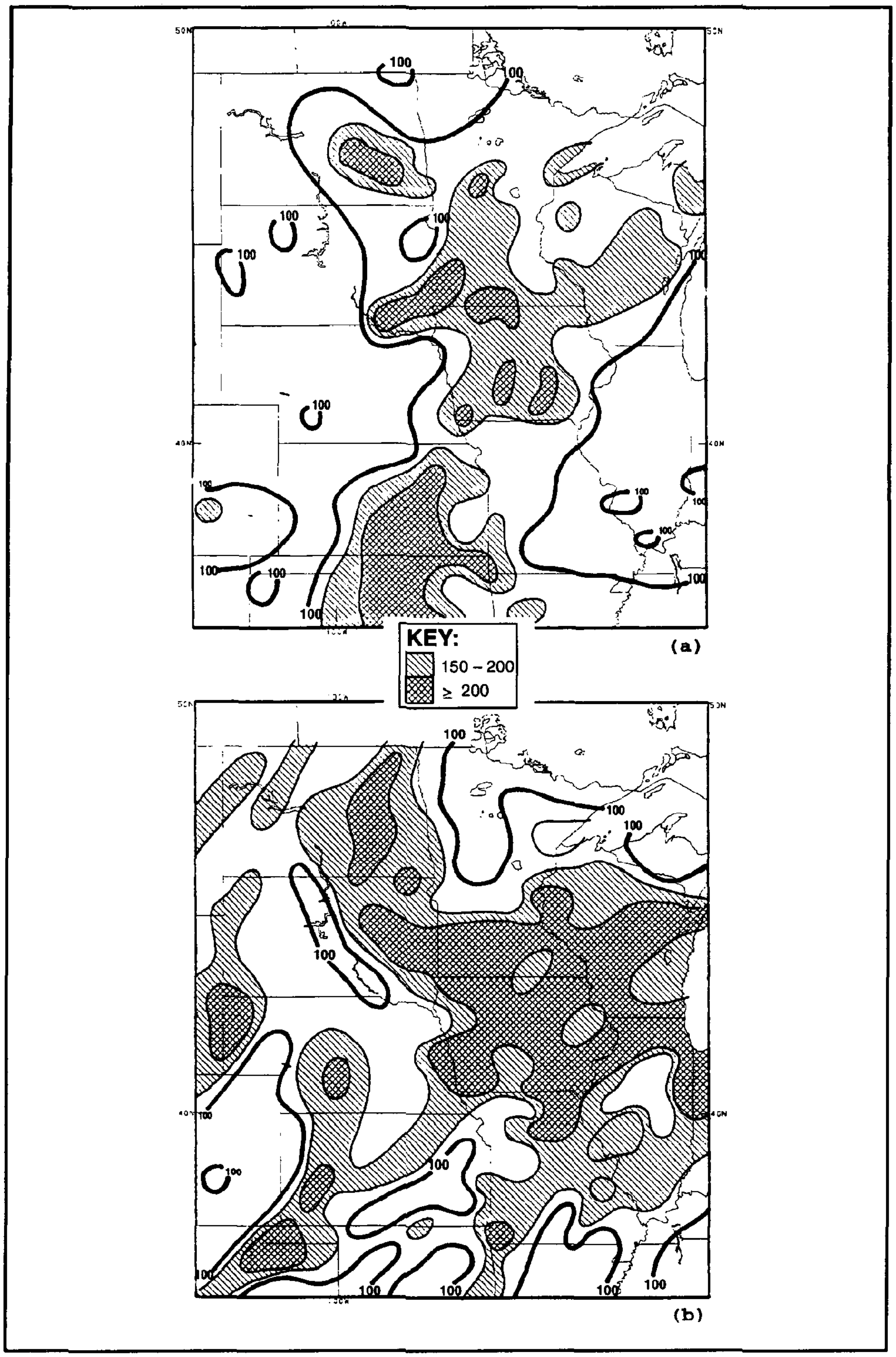


Figure 3-12. *Monthly precipitation as a percent of normal for: (a) May 1993 and (b) June 1993.*

From a seasonal standpoint, above- to much above-average rainfall fell over the entire Upper Midwest from May through August 1993 (Figures 3-12 and 3-13). The May-August 1993 rainfall amount is unmatched in the historical records of the central United States. In July, there were broad areas in North Dakota, Kansas, and Nebraska, as well as a smaller pocket in Iowa, that experienced more than four times normal precipitation. Rainfall amounts, and their return-interval frequencies for selected midwestern states, are listed in Table 3-1. The April-July values are exceptional in all states but Missouri, and the June-July values have return intervals of 75 years or more. The June-July precipitation amounts are remarkable not only in magnitude but also in their broad regional extent. Record wetness existed over 260,000 square miles. The Missouri July values were tempered by below-normal rainfall in the extreme south, although some areas of northwestern Missouri had more than 30 inches of rain in July alone. Seasonal rainfall records were shattered in all nine states.

3.2.4 POSSIBLE CAUSES OF 1993 MIDWEST HEAVY PRECIPITATION

An El Niño/Southern Oscillation (ENSO) episode occurred during 1992 and 1993. In 1992, similar but less intense circulation features were observed; however, no extreme flooding occurred in the United States. Nonetheless, the current, long-lived ENSO event probably contributed to the large-scale atmospheric features associated with the persistent 1993 Mississippi and Missouri River valley flooding.

Table 3-1. *Cumulative precipitation amounts and return periods for several midwestern states.*

STATE	APRIL-JULY		JUNE-JULY	
	Amount (in)	Frequency (years)	Amount (in)	Frequency (years)
Iowa	27.1	300	18.1	260
Illinois	22.9	45	14.7	85
Wisconsin	22.0	200	12.3	75
Minnesota	18.9	70	12.2	100

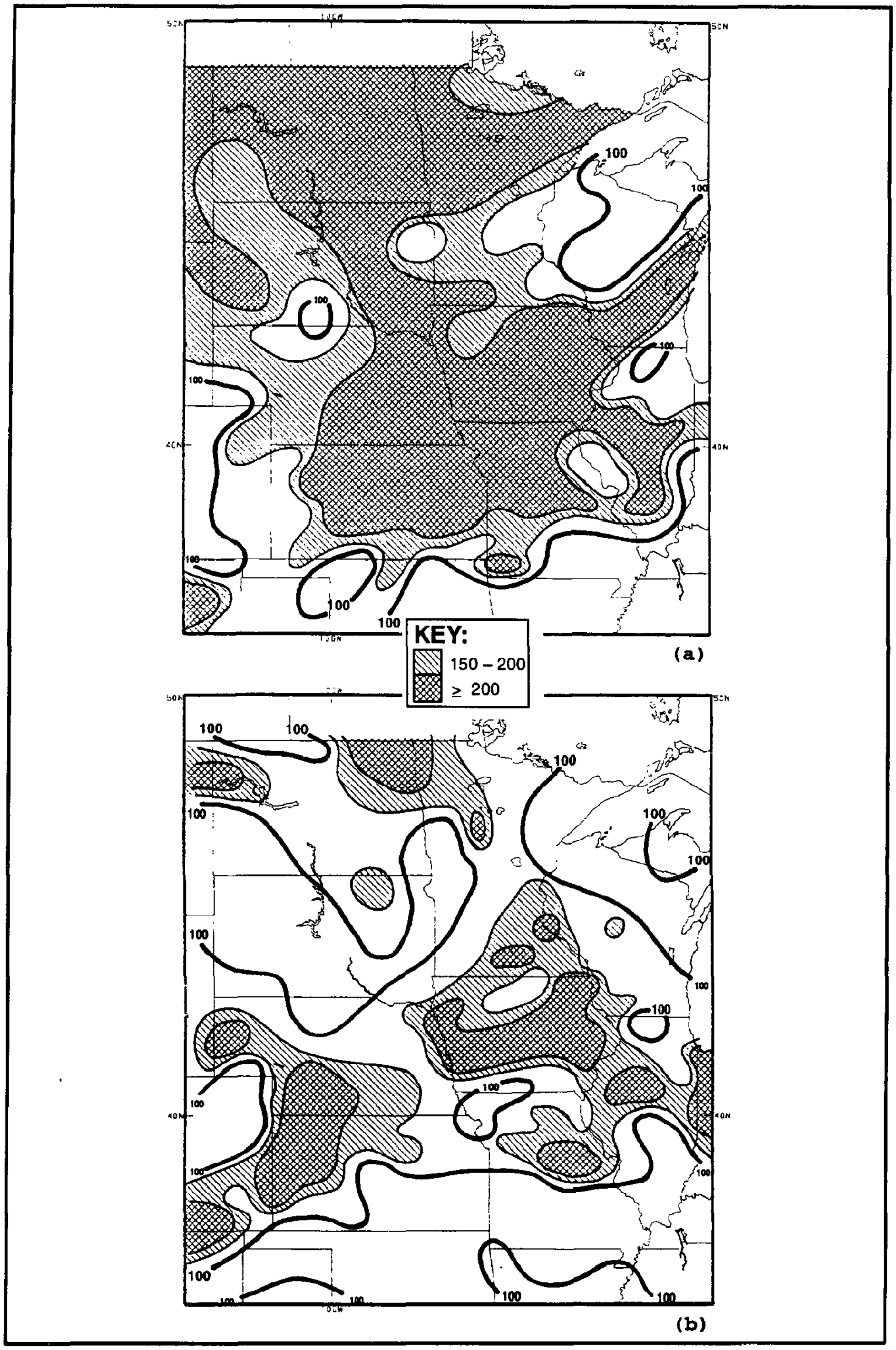


Figure 3-13. *Monthly precipitation as a percent of normal for: (a) July 1993 and (b) August 1993.*

There has been some speculation that the 1993 flooding may have been associated with greenhouse-gas-induced global warming and related circulation changes. Although results from most numerical climate models have suggested that central North America would be drier in a warmer climate, this has also been interpreted as a possible indicator of more variable and extreme weather conditions. Thus, both extreme flooding and extreme drought could be interpreted as being consistent with the global warming hypothesis. Accordingly, the 1993 floods do not add conclusive evidence to the present debate on the possibility of greenhouse gas warming.

In like manner, the eruption of Mt. Pinatubo in June 1991 has likely affected the global mean temperature, but the exact nature of the changes in circulation are not known. It would be difficult to directly link the current Mississippi floods to that, or any other, volcanic eruption. It is only through the entire global heat balance that volcanic aerosols could have an effect on storm tracks and persistent anomalies in the atmospheric circulation. As with the global warming hypothesis, experiments with numerical models in conjunction with further data analysis may shed some light on the role of the Mt. Pinatubo aerosols in shaping the global circulation and specific rainfall patterns.

It may be that the ultimate "cause" of the extreme and persistent precipitation in the central United States is a combination of all the factors discussed above in conjunction with natural variability in the climate system. All of these mechanisms combined, however, seem less likely than the direct influence of the sea surface temperature (SST) anomaly in the tropical Pacific associated with the ENSO.

Preliminary tests using the current ENSO-related SST anomalies in a numerical climate model at the National Meteorological Center show a response in North America that resembles the observed precipitation and temperature anomaly pattern to a considerable extent. It will take more in-depth and thorough analyses involving both observations and coupled ocean/atmosphere global circulation models to get a definitive understanding of the role of the tropical Pacific in the current, extreme precipitation events.

<u>FINDING 3.1:</u> The duration and magnitude of The Great Flood of 1993, as well as its antecedent conditions, strongly support the premise that this event was a significant climate variation rather than simply a sequence of meteorological incidents.	<u>RECOMMENDATION 3.1:</u> Additional analyses of this situation, by both research and operational communities inside and outside of the National Weather Service, should be encouraged. The Great Flood of 1993 should be considered as a climate time-scale variation or anomaly, which may be attributable to a combination of atmospheric, oceanic, and land factors, such as circulation, temperature, soil moisture, and their complex interactions.

3.3 HYDROLOGIC ANALYSIS

Extreme flooding of major river systems like the Mississippi and Missouri Rivers seldom occurs in the summer because of the highly variable nature (in space and time) of convective rainfall in the Midwest, coupled with high rates of evapotranspiration. Typical midwestern summers experience a few localized heavy rain events with as much as 6-12 inches in 1-2 days extending over a few thousand square miles. They are usually randomly distributed, producing localized flash floods on streams and tributaries but are not normally sufficient to produce major river flooding of any consequence.

Another common aspect of the precipitation climate of the midwestern summer involves atmospheric conditions capable of producing above-average rainfall over sizable (state-scale) areas across the Midwest. When these conditions do not occur, the Midwest has summer droughts; an extreme drought occurred in 1988. These "wet periods" typically persist for 2-5 weeks and sometimes last up to 8 weeks, creating the "wet summers" found in the climatic record. Excessively heavy rain extending over wide, multistate areas and lasting more than 8 weeks, however, is a rare event. The combination of long-lasting and spatially extensive wet conditions in the summer of 1993, along with exceptionally wet antecedent hydrologic conditions, were necessary to produce the massive summer flooding of this magnitude and duration.

The Mississippi River flood at St. Louis approached the 100-year return period. The flood return period exceeds the rainfall return period (see Table 3-1) because the flood at St. Louis was the culmination, or combination, of the heavy, record rains on the lower Missouri basin being closely timed with those on the upper Mississippi basin. The floods 200 miles above St. Louis on each river broke historical records; when the rivers merged just above St. Louis, they created an even more exceptional flood.

3.3.1 ANTECEDENT CONDITIONS AND HYDROLOGIC SETTING

Since late in the summer of 1992, conditions were wetter than normal over much of the lower Missouri and upper Mississippi River basins. Minor flooding began as far back as December 1992 in some locations as a result of very heavy November rainfall over the upper Mississippi basin (see Figure 3-4). Soils were very wet at the onset of winter (Figure 3-3(b)). These high moisture levels were locked into the soils as the ground froze.

Although winter precipitation was near normal (Figure 3-4), with moist antecedent conditions, due in large part to the heavy November rains, flooding began in late March with snowmelt. Because of the frozen ground, and then later because of the moist soils, runoff could not be absorbed by the soils. Rivers in the Dakotas, Minnesota, Nebraska, Iowa, Illinois, Kansas, and Missouri rose rapidly. In late March, the National Hydrologic Outlook identified the impacted areas as having "above-average flood potential" (see Figure 3-14).

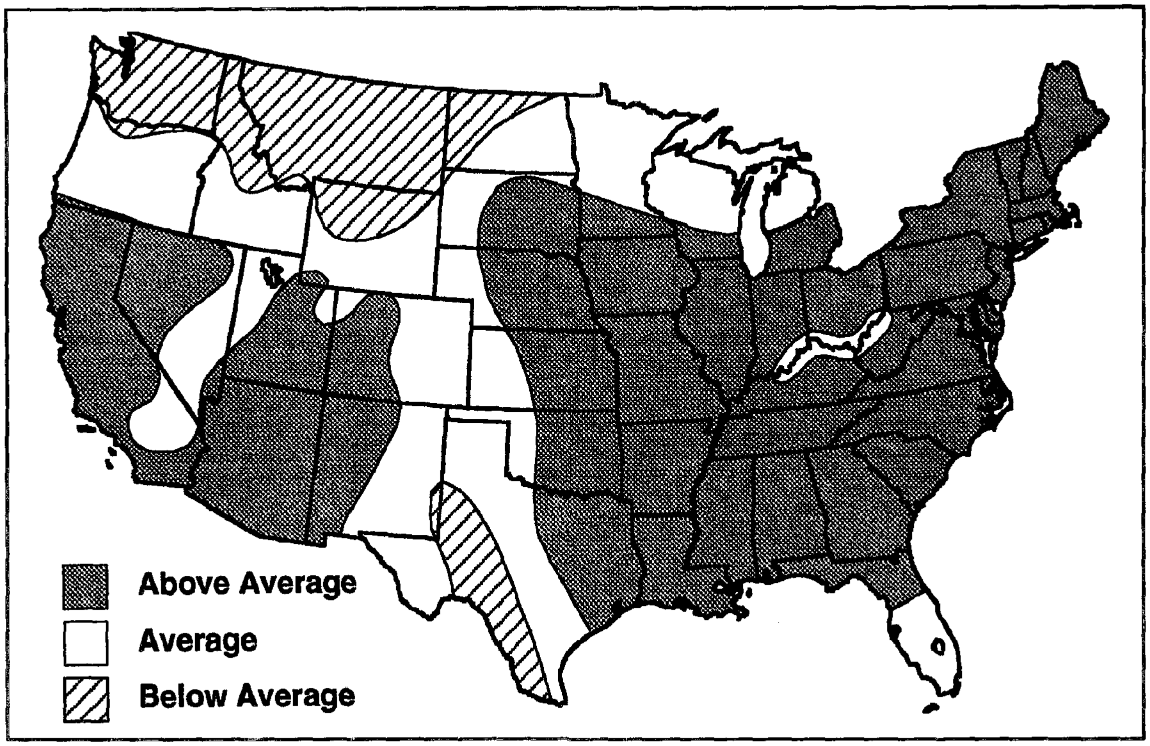


Figure 3-14. *National Hydrologic Outlook issued March 29, 1993, identified above-average flood potential for much of the area affected by The Great Flood of 1993.*

April saw the start of a prolonged period of very wet weather (see Figure 3-4). The period from April through June was the wettest observed in the upper Mississippi basin in the last 99 years. The moisture conditions across the north-central United States on May 1, 1993, can best be described as "saturated." The extremely wet, cool spring of 1993, coupled with normal to above-normal precipitation in the summer, fall, and winter of 1992-93, caused significant spring flooding in the upper Mississippi River basin. Soil moisture conditions, from the surface to a depth of 6 feet, across most of the nine-state region were at "field capacity" (90-100 percent where 100 percent equals field capacity for any given soil type) by the end of May when values are normally less than capacity.

The Midwestern Climate Center, located in Champaign, Illinois, provided maps of plant available moisture (expressed in percentages) at the 12-inch soil depth (Figure 3-15) to illustrate the evolution of the wet soil conditions during the spring and summer of 1993. Values matching field capacity were regionwide on April 1, decreasing somewhat during April as evapotranspiration from new plants and growing crops began to be realized. Note, however, that by June 1 most of the Midwest had values of 100 percent or higher, indicating widespread saturation of most soils due to the extremely heavy May rains.

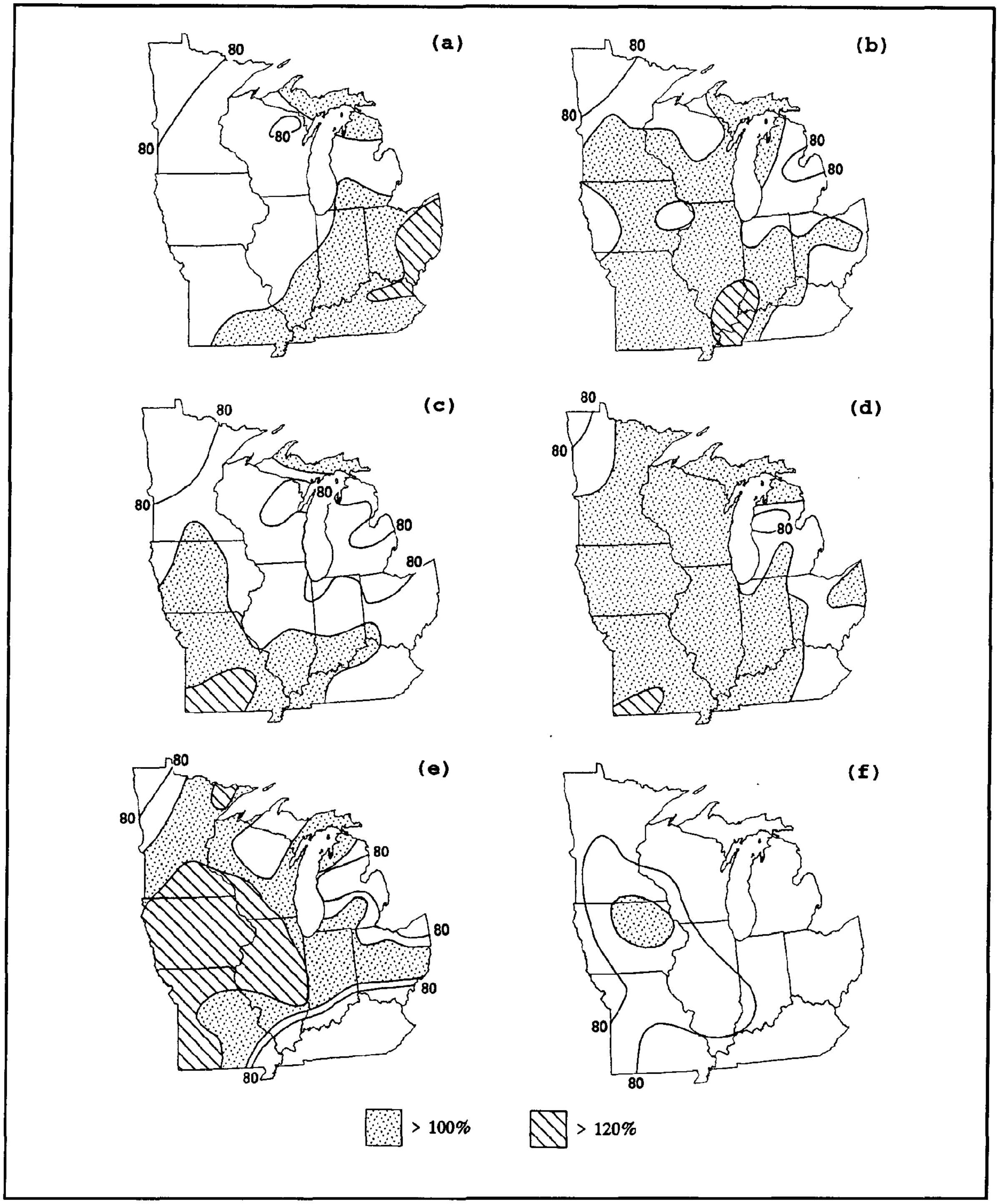


Figure 3-15. *Percent of plant available moisture at 12-inch depth for: (a) March 1, 1993, (b) April 1, 1993, (c) May 1, 1993, (d) June 1, 1993, (e) July 1, 1993, and (f) August 1, 1993.*

In addition, the Midwestern Climate Center has been issuing, on a monthly basis, since the end of August 1993, monthly assessments of soil moisture. When the soil moisture model is coupled with historical climate data for the upper Mississippi River basin, it can provide estimates of the probability of future soil moisture conditions and related flooding potential outlooks for periods during the coming fall, winter, and spring. As indicated in Section 3.3.3, this information will be central to providing early warning of potential flooding in the spring of 1994.

<u>FINDING 3.2:</u> The soil moisture models for the Midwest, operated by the Midwestern Climate Center, can provide a constantly updated assessment of regional soil moisture conditions and a probability of future soil moisture potential critical to an evaluation of longer-term flood potential. In addition, the High Plains and Northeast Climate Centers also provide soil moisture information.	<u>RECOMMENDATION 3.2:</u> The National Weather Service and, in particular, the River Forecast Centers, should obtain soil moisture information from the Regional Climate Centers to enhance near real-time monitoring of hydrologic conditions and to guide preparation of flood potential outlooks. The remaining Regional Climate Centers should be encouraged to consider providing soil moisture information.

3.3.2 REVIEW OF MAJOR FLOODING

The record-breaking, heavy, late-spring/summer rainfall amounts and the ensuing record-breaking summer floods evolved from six factors during the spring and summer of 1993. These factors combined in a unique fashion to cause record-high flows on the lower Missouri and portions of the upper Mississippi Rivers, as well as on many of their tributaries. On June 1, all conditions in the hydrologic cycle favorable for flooding were present:

1. <u>Persistence of Saturated or Nearly Saturated Soils</u>
   Already nearly saturated soils on June 1 (see Figure 3-15) became more saturated during the month. By July 1, when typical midwestern values are 60-70 percent, the plant available moisture values were at total saturation as reflected by the enormous area of 120 percent or higher across Iowa, much of Missouri, central and northern Illinois, southwestern Wisconsin, and southern Minnesota. Values by August 1 were still abnormally high (50-60 percent is typical), indicating that near saturated soils prevailed in a large, northwest-southeast zone paralleling the upper Mississippi River.

2. <u>High Incidence of Rain Events</u>
   A critical factor affecting the record flooding was the near continuous nature of the rainfall. Many locations in the nine-state area experienced rain on 16-22 days in July, compared to an average of 8-9 days with rain. There was measurable rain in parts of the upper Mississippi basin on every day between late June and

late July. The persistent, rain-producing weather pattern in the Upper Midwest (see Figure 3-6), often typical in the spring but not summer, sustained the almost daily development of rainfall during much of the summer.

3. Large-Sized Rain Areas

The semi-stationary nature of the convectively unstable frontal conditions across the Upper Midwest from June through early August not only caused the near continuous occurrence of daily rains but also frequently created extensive areas of moderate to heavy rains. Frequently, a day in June or July 1993 would have rain areas that were 100-200 miles wide and 400-600 miles long (typically about 75,000 square miles) across parts of the nine-state area. Most of these rain areas included zones with 1-2 inches of rain over 5,000-15,000 square miles. An excellent example of such rain areas is the isohyetal map of July 7 rain across central Missouri (Figure 3-16). A few such large-sized areas of convective rainfall normally occur in most midwestern summers, but their high frequency in 1993 (at least 73 such cases) with quite large dimensions capable of affecting both the Missouri and Mississippi River basins was exceptional.

4. Orientation of Rain Areas

Several multi-day periods in June and July had large rain areas (see previous section) that were oriented along the major rivers. In late June, several large rain areas were aligned northwest-southeast over the Mississippi River from northern Illinois into central Minnesota. Then, in early July, similar systems became aligned southwest-northeast along the Mississippi's course from Quincy, Illinois, to southern Wisconsin, at the time the flooding was maximizing in this reach of the river. In early to mid-July, several large rain areas were oriented west-east along the Missouri River and across Missouri. Such alignments deposited enormous amounts of water directly into the main stems of the rivers without any delay for runoff and in-stream storage in the tributaries.

5. Extremely Large Number of Localized Heavy Rains Capable of Producing Flash Floods

Intermixed with the frequent incidence of large areas of moderate to heavy rainfall, as described in (2) and (3) above, were many intense rainstorms having "flash flood" characteristics. These rainstorms are defined here as discrete areas, typically 1,000-5,000 square miles in size, where as much as 6-12 inches of rain falls in 24 hours or less. The isohyetal map of the large July 7 rain area across central Missouri (Figure 3-16) contains three such intense, 6-inch centers. Another version of this type of storm is depicted in the isohyetal map for a 4-hour rainstorm that occurred in south-central Wisconsin on July 18 (Figure 3-17). The early count of such storms indicates that at least 175 occurred in the nine-state area of excessive flooding from early May through August. This number of intense, short-lived rainstorms is probably a record for the Upper Midwest.

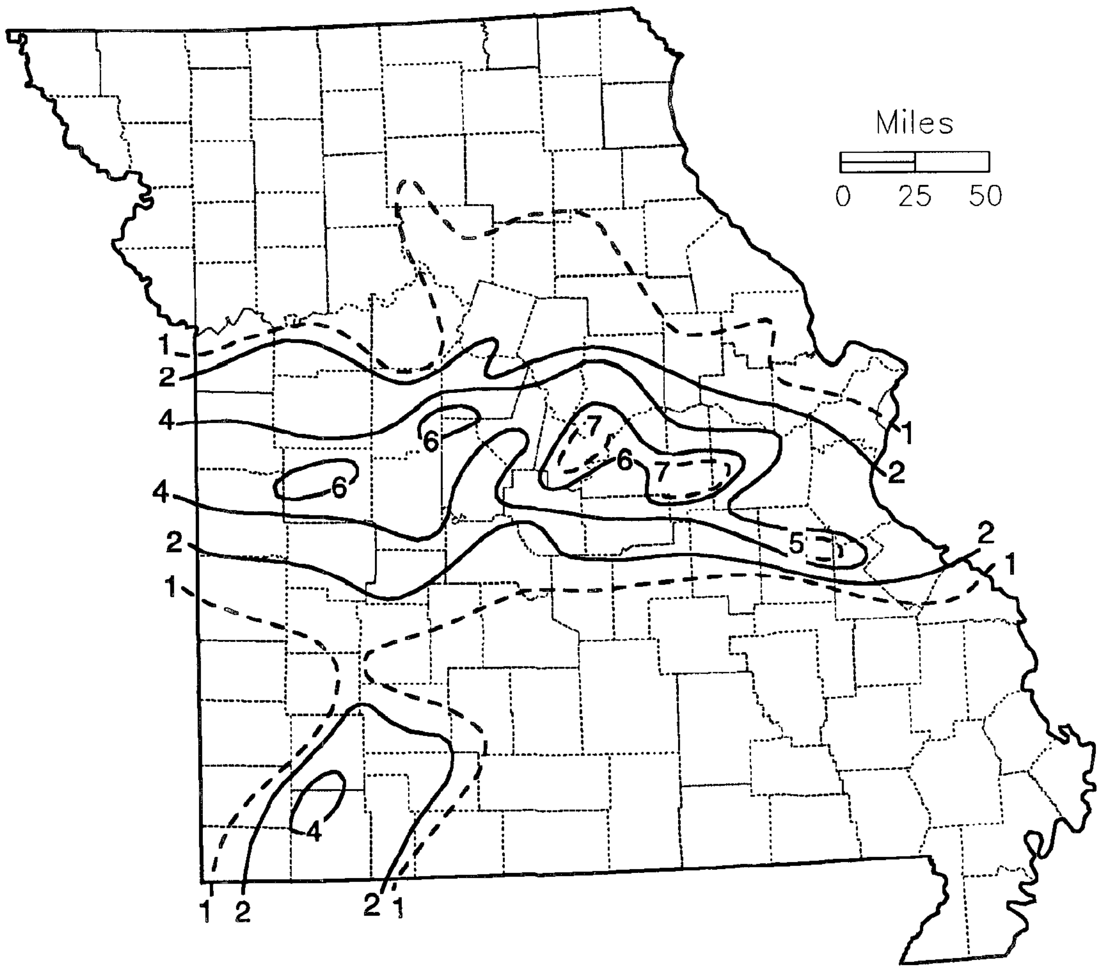


Figure 3-16. *Analysis of total observed precipitation in central Missouri for the 24-hour period ending 7 a.m. CDT, July 7, 1993.*

6. Seasonal Evapotranspiration Below Normal

The near continuous cloud cover of the June-August period (50 percent of the days were cloudy compared to a normal of 20 percent), coupled with temperatures which were 2-3 degrees below average and a very moist lower atmosphere, reduced actual evapotranspiration to below-normal levels. This reduced the upward movement of moisture from the soil and increased the flood potential.

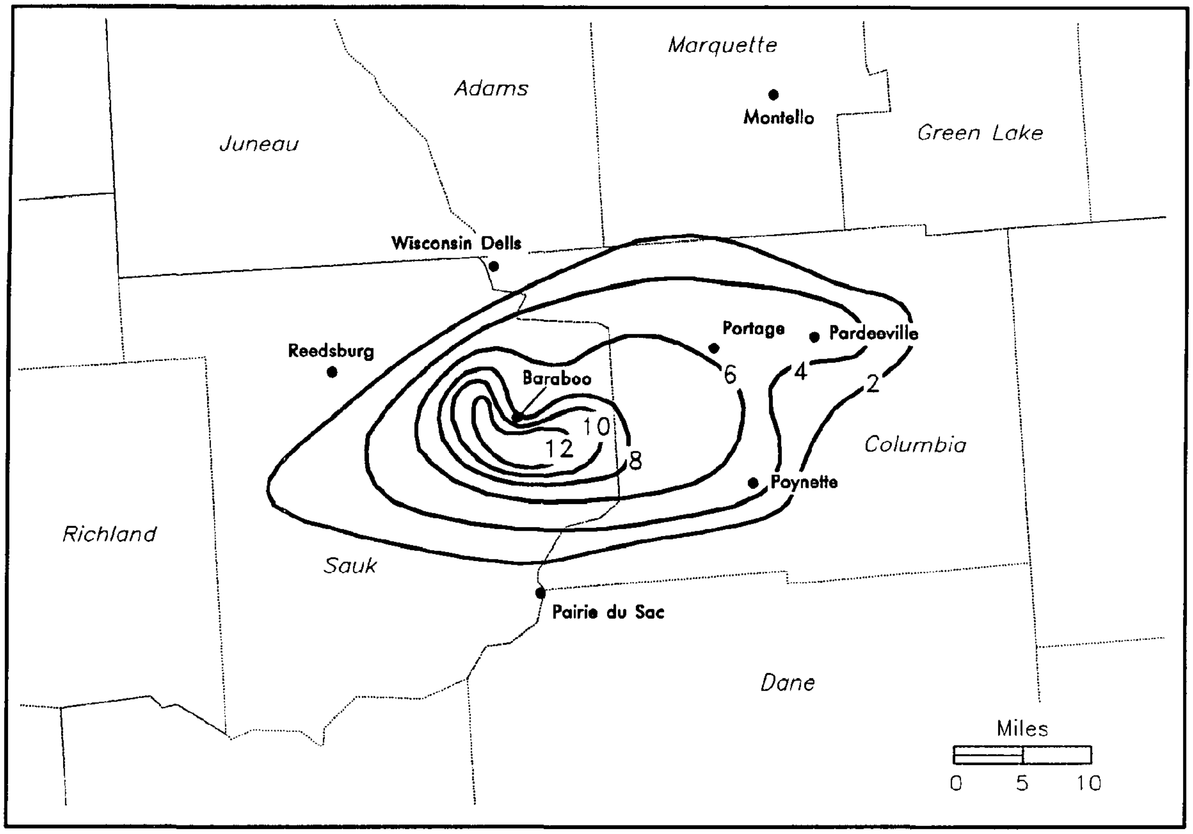


Figure 3-17. *Analysis of 24-hour precipitation event ending at 7 a.m. CDT on July 18, 1993, in south-central Wisconsin. Most rain fell in 4 hours or less.*

In summary, the genesis of The Great Flood of 1993 had been set by June 1 with saturated soils and filled streams across the Upper Midwest. The water from the ensuing persistent heavy rains of June, July, and August had no place to go other than into the streams and river courses. Record summer rainfalls with amounts achieving 75- to 300-year frequencies thus produced record flooding on the two major rivers, equalling or exceeding flood recurrence intervals of 100 years along major portions of the upper-Mississippi and lower Missouri Rivers.

3.3.2.1 MAJOR FLOODING IN JUNE

Rainfall during the first half of June was typical of late-spring conditions in the upper Mississippi and lower Missouri basins: scattered pockets of heavy, convective precipitation. As discussed throughout Section 3.2 above, in mid-June a stable, high amplitude, upper-level pattern, more typical of late-winter or early-spring conditions, created persistent, excessive rain over much of the Upper Midwest. Major flooding began after a particularly heavy rainfall period (June 17-20; see Appendix B, Section B.2.2.1) in southwest Minnesota and northwest Iowa. This included record flooding on the Minnesota River.

The next major precipitation impulse occurred June 23-25. This water combined with flood flows from the Minnesota River to initiate the first major flood crest that moved down the Mississippi.

3.3.2.2 MAJOR FLOODING IN EARLY JULY

Following a short, dry period, a prolonged siege of heavy rainfall extended from June 30 to July 11. This included extreme precipitation on July 9 in Iowa, which resulted in record flooding on the Raccoon and Des Moines Rivers (see Appendix B, Section B.2.2.2). Just as the crests from these two rivers reached Des Moines, a relatively small, convective pocket dumped several inches of rain on the crests rapidly boosting the river levels and flooding a water treatment plant. This rainfall event also led to record flooding on portions of the lower Missouri River and combined with the crest already rolling down the Mississippi, ensuring record river stages from the Quad Cities area, through St. Louis, and as far south as Thebes, Illinois.

3.3.2.3 MAJOR FLOODING IN LATE JULY

Another major precipitation impulse occurred July 21-25 (see Appendix B, Section B.2.2.3). The heaviest rains were focused farther south than the earlier events, with especially heavy rain falling over eastern Nebraska and Kansas, leading to second major crests on both the Missouri and Mississippi Rivers. An example of the river stages at Kansas City is shown in Figure 3-18. The hydrograph at the Quad Cities (Figure 3-19) shows only a single crest, demonstrating the generally southern focus of this second event. At St. Louis, both crests are clearly evident in the hydrograph (see Figure 3-1). While flooding did not extend as far upstream on the Mississippi, new record crests were observed at many locations downstream, as well as on much of the portion of the Missouri River that flows through the state of Missouri.

The crests on the Missouri and Mississippi Rivers are summarized in Figure 3-20. The solid squares in both Figure 3-20(a) for the Missouri River and Figure 3-20(b) for the Mississippi River show the previous floods of record. The highest stage reached on each river during the first record-breaking crest in early to mid-July is indicated by the solid line. Similarly, the dashed line is the highest level reached during a second flood wave that occurred in the later part of July and into early August. On the Missouri River, the second flood wave was higher than the first at most locations south of Omaha, where many new records were set. The river levels of the two flood waves were more similar on the Mississippi River. Every gage, from the Quad Cities to below St. Louis, set new, all-time record stages!

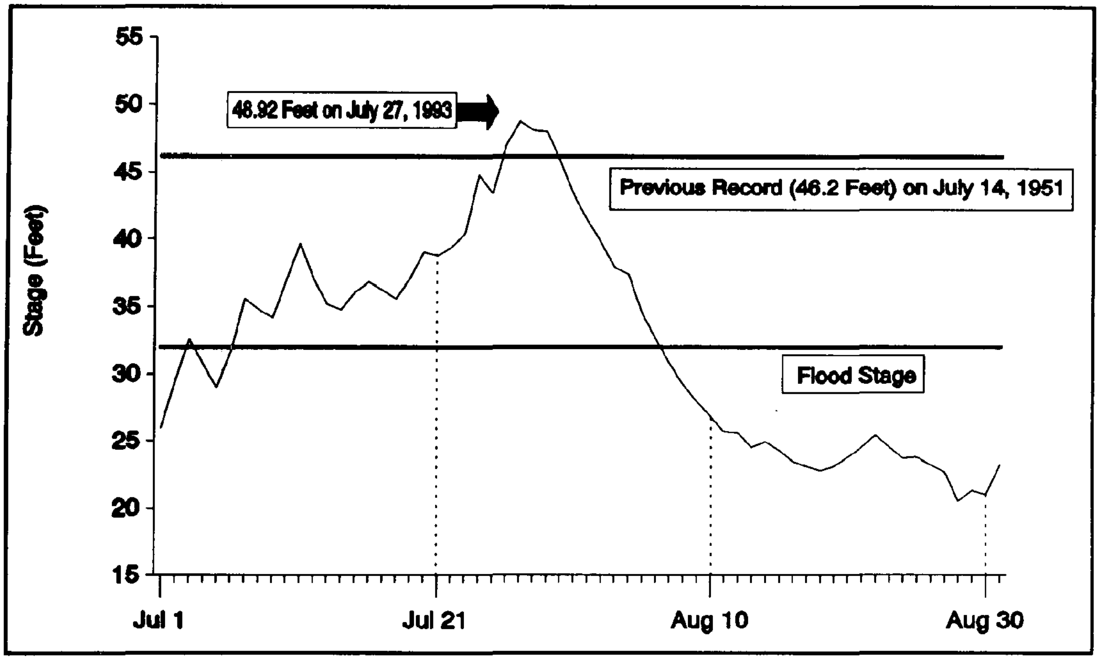


Figure 3-18. *Hydrograph for Missouri River at Kansas City, Missouri.*

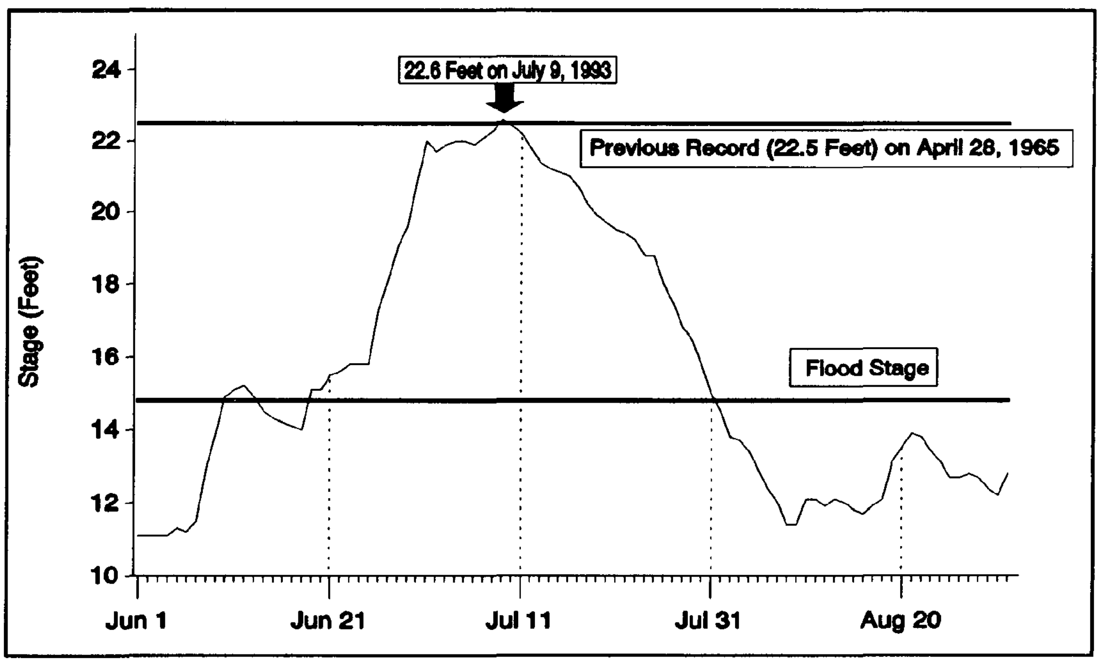


Figure 3-19. *Hydrograph for Mississippi River at Quad Cities.*

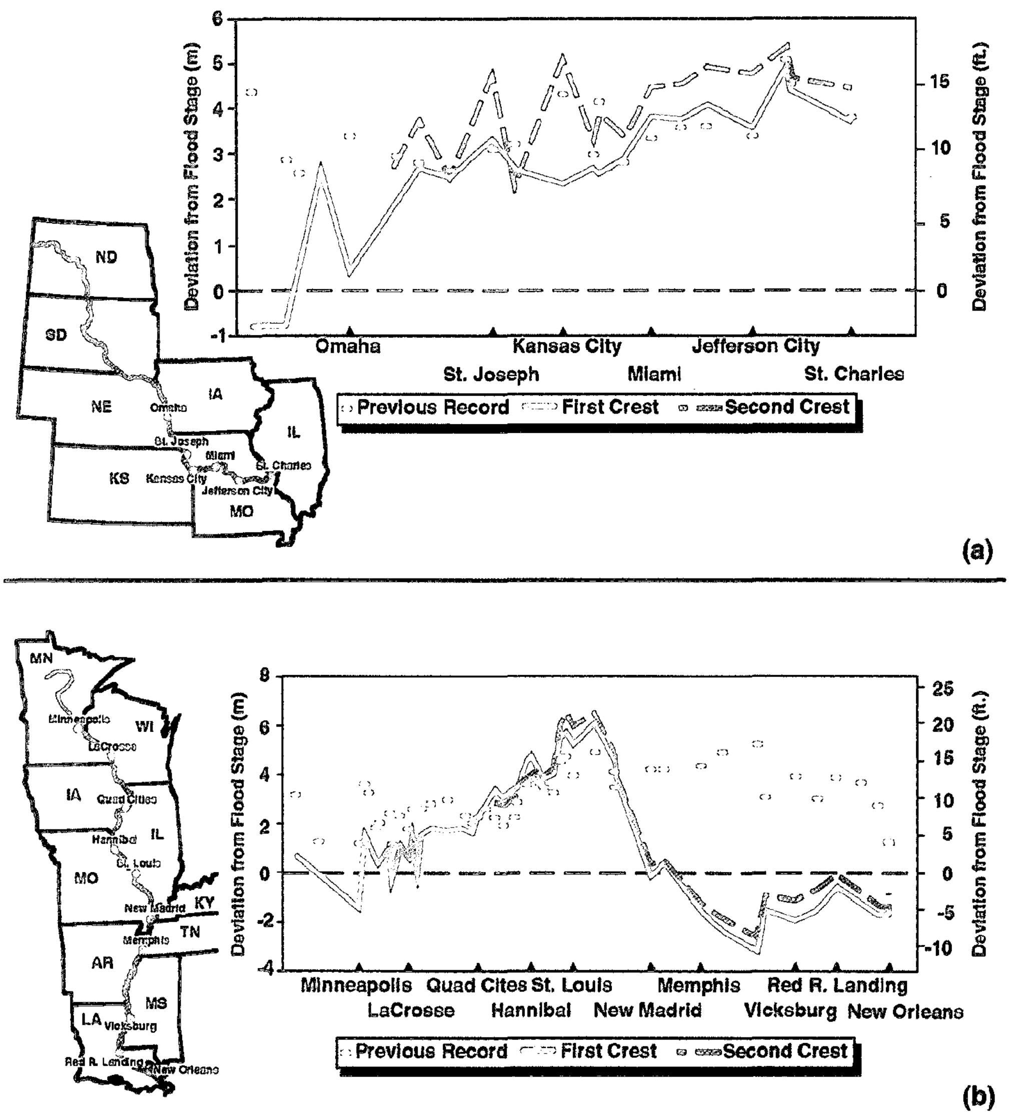


Figure 3-20. *Summary of flood crests on the (a) Missouri and (b) Mississippi Rivers during The Great Flood of 1993.*

A striking feature of Figure 3-20(b) is the rapid drop in the flood crest about 200 miles south of St. Louis. The large channel capacity of the Mississippi below the confluence with the Ohio River contributed to this dramatic reduction as the crests moved into the lower part of the Mississippi River (see Figure 3-21). The first four bars in Figure 3-22 show the normal seasonal variation of discharge in the Mississippi River system and the relative contributions of the major tributaries to flow at the mouth of the river as it empties into the Gulf of Mexico. While flows in the upper portion of the Mississippi basin were record breaking (about five times the seasonal norm at St. Louis on August 1, as shown in the right bar in Figure 3-22), the discharge on the lower Mississippi was only modestly higher than typical springtime flows but more than twice the seasonal average.

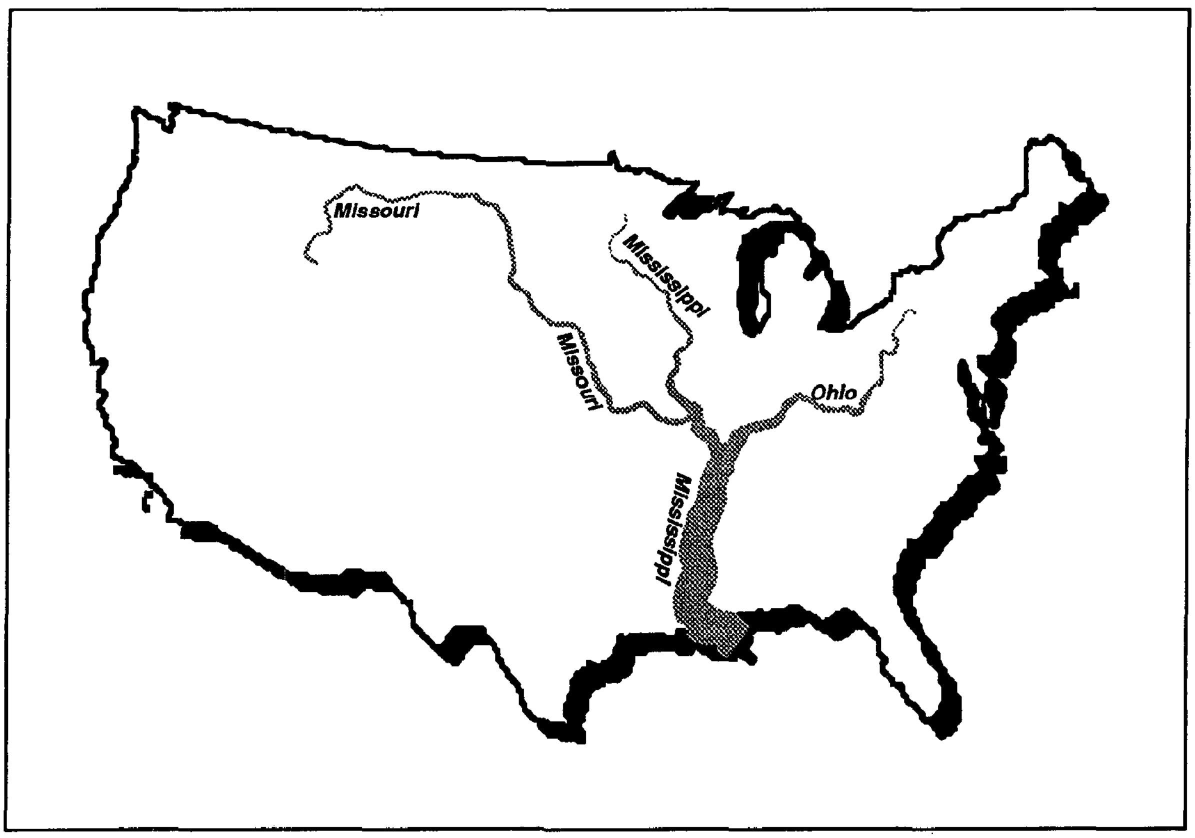


Figure 3-21. *Schematic showing typical relative contributions to flow of large rivers in the Mississippi River system.*

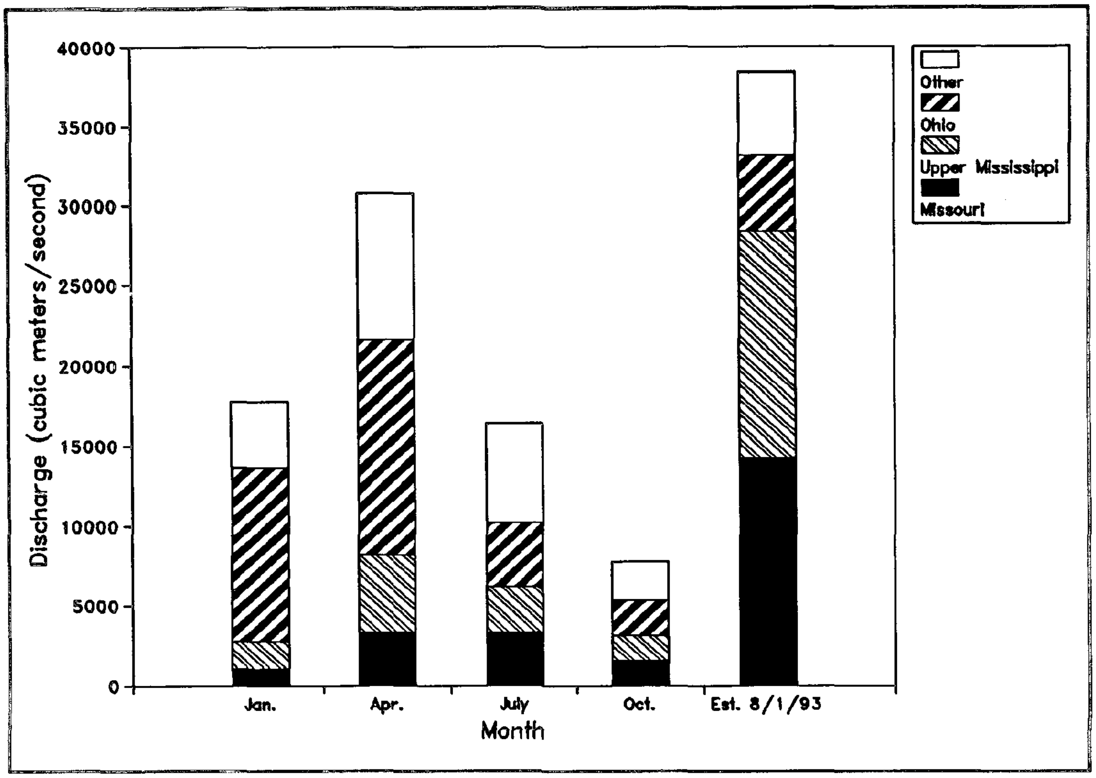


Figure 3-22. *Normal annual variation of discharge near the mouth of the lower Mississippi River compared to the discharge on August 1, 1993 (right bar), which includes the exceptional flow from both the Missouri and upper Mississippi Rivers.*

3.3.2.4 FLASH FLOODING

Flash flooding is a rapid, localized rise in water levels in smaller streams or in low spots. While flash flooding can be caused by ice jams and dam breaks, it most commonly occurs as a result of intense, shorter-duration, convective rainfall. As mentioned above, The Great Flood of 1993 included numerous precipitation events that would typically be associated with flash flooding. However, as is the case in quite a few major floods, the distinction between flash flooding--short duration (6-12 hours) and smaller areal extent (several hundred square miles)--and major river flooding becomes blurred. During the summer of 1993, many of the events with rainfall intensities typical of flash flooding were far more widespread and lasted considerably longer than "classical" flash floods. Indeed, The Great Flood of 1993 (and other historical floods) can be considered to result from the cumulative effect of unusual numbers of substantial flash flood events (combined with anomalous antecedent climatological conditions). There were at least 15 flash floods that caused dam breaks; the majority occurred in Wisconsin during The Great Flood of 1993.

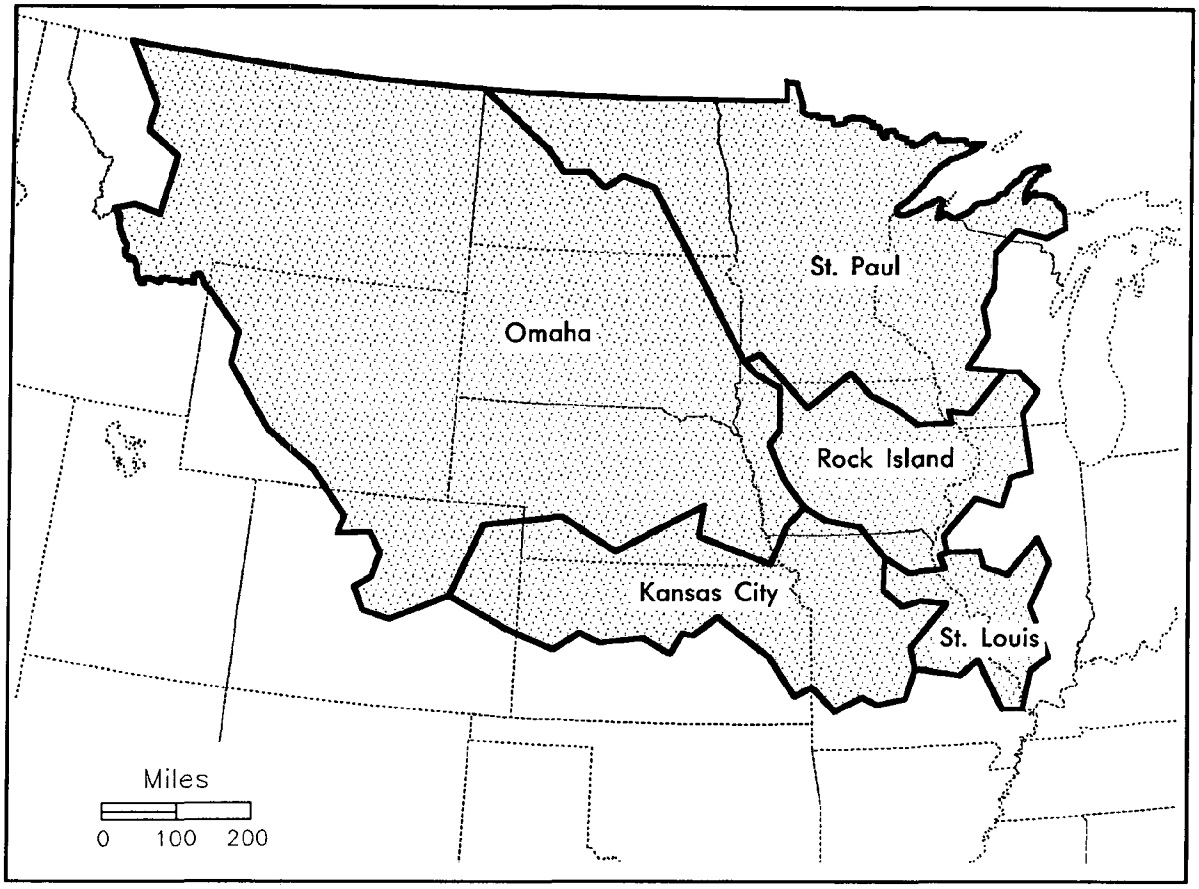


Figure 3-23. *Corps of Engineers Districts and their boundaries.*

3.3.2.5 WATER CONTROL STRUCTURES

Flood Control Reservoirs

Throughout the upper Mississippi and Missouri River basins, 66 flood control reservoirs exist. Many of the reservoirs were developed for flood control purposes but were not designed for the magnitude of The Great Flood of 1993. For example, inflow into the U.S. Army Corps of Engineers (COE) Coralville Reservoir, located in Iowa, during the summer of 1993 was several times its total storage capacity. Reservoir storage was quickly maximized during the early portion of The Great Flood of 1993. Persistent, heavy rain led to uncontrolled discharges over spillways of some reservoirs during the later stages of the flood.

A major exception to the pattern of overfilled reservoirs occurred in the upper reaches of the main stem of the Missouri River basin, where the COE operates six enormous reservoirs for multiple purposes. When operated for flood control, these projects provided relief to the downstream reaches of the Missouri River by releasing less water than normal. One benefit associated with The Great Flood of 1993 was that additional amounts of water retained in the upper reaches of the Missouri River refilled the main projects ending the long-standing drought effects.

Levees

Many people made valiant efforts to prevent levees from overtopping on the Red River of the North, upper Mississippi, and Missouri River basins. Farmers, residents of both small and large towns, COE employees, out-of-state volunteers, Emergency Management Agencies, and contractors spent countless hours struggling to protect homes, farms, towns, bridges, and cities. In spite of these efforts, as shown in Table 3-2, 18 percent of Federal levees and 78 percent of the non-Federal levees failed or were overtopped. The districts identified in Table 3-2 are shown in Figure 3-23. The difference in the failure rate is due to the fact that most Federal levees are designed to withstand a 100-500 year flood, while non-Federal levees, predominantly protecting agricultural lands, are frequently designed for a flood with return periods of 50 years or less. Such a failure rate for a flood such as The Great Flood of 1993 is not surprising.

Table 3-2. *Distribution of levee failures by Corps of Engineers Districts.*

COE DISTRICT	NUMBER OF FAILED OR OVERTOPPED LEVEES	
	Federal	**Non-Federal**
St. Paul	1 of 32	2 of 93
Rock Island	12 of 73	19 of 185
St. Louis	12 of 42	39 of 47
Kansas City	6 of 48	810 of 810
Omaha	9 of 31	173 of 210
Totals	40 of 226	1043 of 1345

Note: In some cases, a single levee has been divided into a series of levees according to local levee district and is counted as more than one levee.

It is noteworthy to mention the flood-fighting efforts that took place in the COE Rock Island District. Major levee systems were saved by scalping dirt landward of the levee and compacting it on top of the levee. Flash boards made of plywood and supported on the dry side of the levees provided an additional 4 feet of protection.

The COE has begun damage assessment directed by Public Law 84-99 to determine the cost of rehabilitating levees governed by this law. Under this authority, the COE may rehabilitate publicly sponsored flood control projects damaged or destroyed by floods to their pre-flood condition. Congress has appropriated $120 million to perform Public Law 84-99 activities.

3.3.3 FUTURE FLOOD POTENTIAL

A central issue for responding to and recovering from The Great Flood of 1993 is the potential for future flooding in the flooded areas. Floods of almost any dimension would be detrimental to efforts in rebuilding levees, highways, homes, towns, and even in raising crops in 1994.

At the end of August 1993, soil moisture remained well above normal throughout most of the nine-state area. While some grain crops were harvested in 1993, the summer's grain production was seriously depressed. Evapotranspiration and surface runoff were inadequate to restore conditions to normal as winter approached.

Flooding could easily occur if a period of heavy rain develops in parts of either basin. The onset of winter with above-normal soil moisture conditions presents a situation very conducive to spring snowmelt floods. If the amount of winter precipitation is normal or above, spring flooding in the Upper Midwest in 1994 is quite likely.

CHAPTER 4

HYDROLOGIC AND HYDRAULIC FORECAST METHODOLOGY

4.1 INTRODUCTION

Operational software systems required to generate hydrologic forecasts for river basins of the magnitude of the Missouri and upper Mississippi Rivers, as well as the Red River of the North, are extremely complex. The National Weather Service River Forecasting System (NWSRFS) contains a variety of models, procedures, and techniques. This chapter describes the hydrologic and hydraulic components included in operational river forecasting systems, the methodology used to forecast river stages during The Great Flood of 1993, and the forecast methodology that is planned for the future.

4.2 PHYSICAL DESCRIPTION OF MAJOR RIVER BASINS AFFECTED BY THE GREAT FLOOD OF 1993

The upper Mississippi River basin, located in the north-central United States, extends about 775 miles south from its headwaters in Minnesota and stretches in width about 650 miles from northeastern South Dakota to northwestern Indiana (see Figure 4-1). The length of the upper Mississippi River is 1,366 miles with a drainage area of 189,000 square miles. The basin covers parts of eight states (Minnesota, Illinois, Iowa, Wisconsin, Missouri, Indiana, South Dakota, and Michigan) but does not include the Missouri River and its tributaries. From its headwaters in Lake Itasca to Minneapolis-St. Paul, the Mississippi River drops at an average rate of almost 2 feet/mile. From Minneapolis-St. Paul to Cairo, Illinois, the Mississippi has an average slope of only 0.6 foot/mile. Table 4-1 lists the major tributaries of the Mississippi River and their drainage areas. The North Central River Forecast Center (NCRFC) in Minneapolis, Minneota, is responsible for forecasting the upper Mississippi River basin.

The Red River of the North is formed at the confluence of the Otter Tail and Bois de Sioux Rivers below the cities of Wahpeton, North Dakota, and Breckenridge, Minnesota. The river flows north for about 400 miles before reaching the United States-Canadian international boundary where it continues north into Canada. Drainage into this river includes parts of North Dakota, South Dakota, Minnesota, and Manitoba, with 40,200 square miles of the basin located in the United States. Most of the basin is extremely flat. The NCRFC is responsible for forecasting the parts of the Red River basin located in the United States.

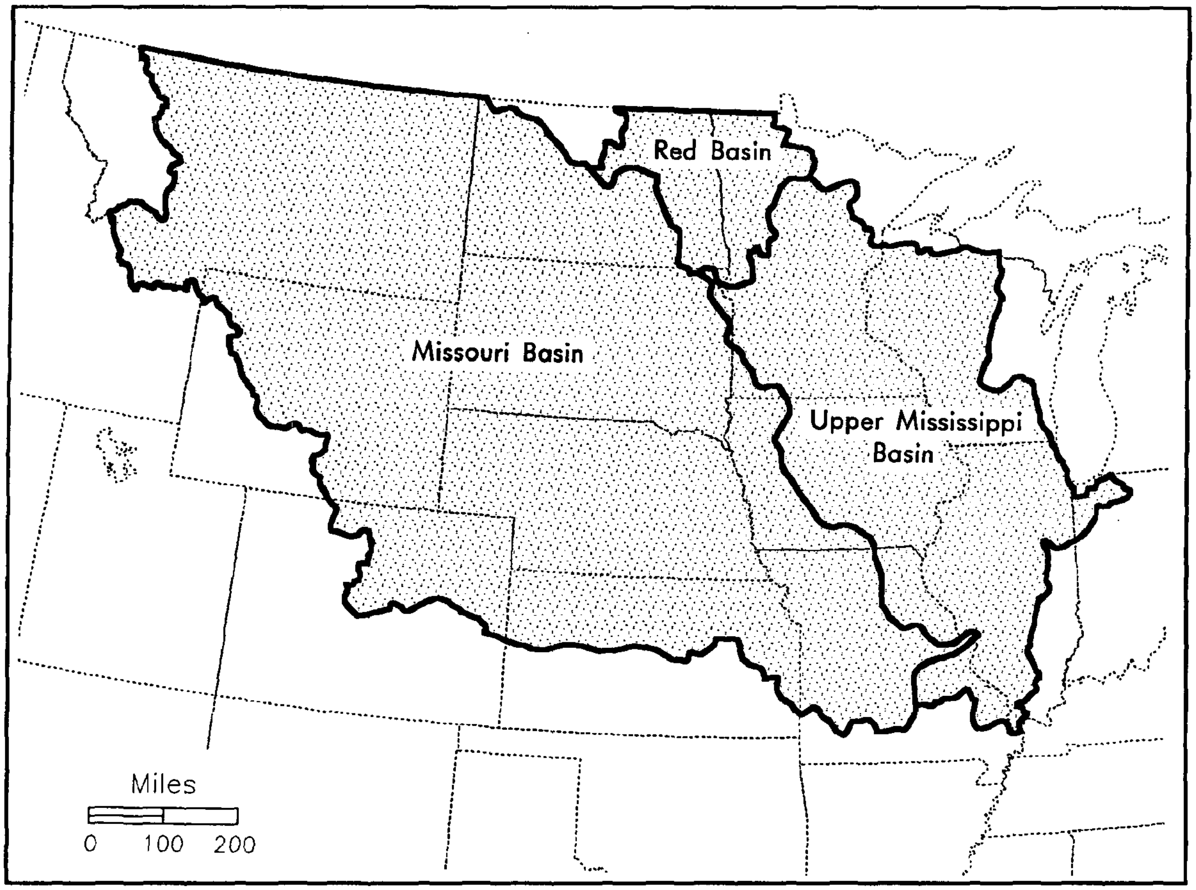


Figure 4-1. *Areal extent of the Missouri River, Red River of the North, and upper Mississippi River basins.*

The Missouri River flows over 2,460 miles from its beginning at the confluence of the Gallatin, Madison, and Jefferson Rivers in Montana to its confluence with the Mississippi River just above St. Louis, Missouri. Draining all or parts of 10 states (Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, and Missouri), it has a total drainage area of 529,350 square miles, which represents more than 42 percent of the total area drained by the Mississippi River system. Table 4-2 lists the major tributaries of the Missouri River and their drainage areas. With a total fall of 3,630 feet, the slope of the Missouri River is mild (0.2-4.3 feet/mile) with an average of 1.5 feet/mile. Except for the Milk River, every major tributary in the upper and middle portions of the basin is a right bank (looking downstream) tributary flowing to the east or the northeast. Storms that typically move in an easterly direction can potentially cause a large concentration of flows. The Missouri Basin River Forecast Center (MBRFC) in Kansas City, Missouri, is responsible for forecasting the Missouri River basin.

Table 4-1. *Major tributaries of the Mississippi River and their drainage areas.*

TRIBUTARY	DRAINAGE AREA (SQ.MI.)	TRIBUTARY	DRAINAGE AREA (SQ.MI.)
Minnesota	16,920	Rock	10,850
Cannon	1,420	Skunk	4,325
Chippewa	9,480	Des Moines	14,540
Zumbro	1,402	Fox	502
Black	2,390	Wyaconda	458
Root	1,670	Fabius	1,570
Iowa	4,770	Salt	2,920
Cedar	7,870	Illinois	28,200
Wisconsin	11,705	Kaskaskia	5,840
Turkey	1,696	Big Muddy	2,360
Maquokata	1,903	Meremac	3,980
Wapsipinicon	2,563		

Table 4-2. *Major Missouri River tributaries with drainage areas of 6,000 square miles or more.*

TRIBUTARY	DRAINAGE AREA (SQ.MI.)	TRIBUTARY	DRAINAGE AREA (SQ.MI.)
Jefferson River	9,277	South Platte River	24,300
Milk River	22,332	Loup River	15,200
Powder River	13,194	Elkhorn River	6,900
Yellowstone River	69,103	Platte River	85,800
Little Missouri River	8,310	Republican River	24,542
		Smokey Hill River	19,261
Cheyenne River	24,500	Big Blue River	9,640
James River	21,500	Kansas River	60,060
Big Sioux River	9,810	Grand River	7,883
Niobrara River	12,600	Osage River	14,500
North Platte River	34,900		

The Red, upper Mississippi, and Missouri River basins have a number of hydraulic structures including reservoirs for flood control, water supply, power generation, and recreation; locks and dams for navigation; transmountain diversions; and flood control levees. The upper Mississippi River, from St. Anthony Falls in Minneapolis-St. Paul to St. Louis, has a 9-foot minimum depth navigational channel. This depth is maintained by a system of 27 locks and dams, which have minimal effect on flood control efforts. Of the 14,000 dams in the Missouri River basin, 70 have a significant affect on streamflow and, consequently, are accounted for by MBRFC in its forecast schemes. Major reservoirs operated by the U.S. Army Corps of Engineers (COE) on the Missouri River ensure flows sufficient to maintain navigation from its confluence with the Mississippi to Sioux City, Iowa. A total of 226 Federal and 1,576 non-Federal flood control levees are located throughout the three basins. Because the Red River drainage is so flat, diversion structures are necessary to carry water from agricultural land into drainage ditches which carry the water to the river.

The Red, Mississippi, and Missouri River systems encompass several complex hydrologic and hydraulic conditions, including some created by The Great Flood of 1993, that challenge river forecasters' abilities. Heavy rainfall in concentrated areas may cause flash flooding. On very flat rivers (e.g., the Red) small changes in stages may cause overland flow for miles. In a system where levees are being overtopped and/or breached throughout, it is very difficult to account for the volumes of water (which determine the discharge to downstream points) that are in the rivers at any given time. Additionally, backwater conditions along tributaries, changes in the river bed from sedimentation, and locally stored water in inactive floodplain areas may also cause significant forecasting problems.

4.3 RIVER FORECASTING OVERVIEW

The basic steps in forecasting streamflow can be simplified as:

1. Use observations (precipitation, temperature, etc.) to estimate the net amount of water entering the basin from rainfall and/or snowmelt. If precipitation forecasts are available, they may also be used as input. Larger basins are typically broken into smaller subbasins where the assumption of uniformity of the precipitation, temperature, and basin hydrologic characteristics is more likely to be valid.

2. Convert the net input of water (from rainfall or snowmelt) into a volume that enters the stream (runoff), accounting for surface slope, soil characteristics, soil moisture, infiltration, evaporation, etc. The inflow into a stream causes it to rise. A plot of the time variation of the stream level or volume of water flowing past an observation point is called a hydrograph (e.g., Figures 3-1, 3-18, 3-19).

3. Calculate the volume rate of water (discharge) that flows from a point in the stream to points farther downstream. The process of calculating this flow from one point along a stream to another is called routing.

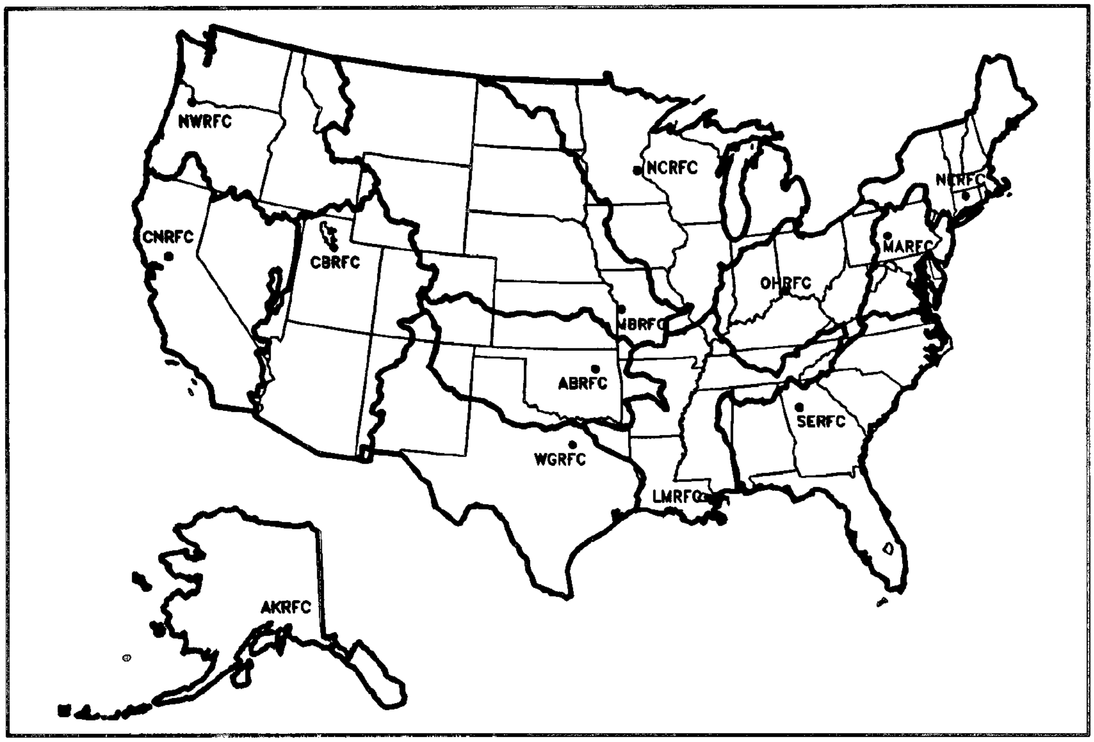


Figure 4-2. *Locations of, and areas served by, the 13 NWS River Forecast Centers.*

4.3.1 NATIONAL WEATHER SERVICE RIVER FORECASTING SYSTEM

The objective of river forecasting is to predict water levels (stages) at specific locations along a river by simulating various components of the hydrologic cycle. A river forecasting system should include: (1) hydrometeorological data analysis procedures to determine the areal distribution of precipitation, temperature and evaporation; (2) hydrologic models to compute the amount of runoff; and (3) hydraulic models to account for the movement of water down the channel system. For large areas (such as those forecast by the NCRFC and MBRFC) with many data collection stations and forecast points, a river forecast system also requires efficient procedures for managing large amounts of information, as well as a user interface that allows the forecaster to easily select from available options and to adjust the models based on observations and hydrologic insight.

The National Weather Service (NWS) supports, at a national level, an operational river forecasting capability known as the NWSRFS. The NWSRFS was released in the mid-1980s for implementation by the 13 River Forecast Centers (RFC) shown in Figure 4-2. The NWSRFS is now being used completely by seven RFCs for operational forecasting, while the other six offices are in varying stages of making the transition from their locally developed

Table 4-3. *Selected models available in the NWS River Forecast System.*

FUNCTION	TYPE OF MODEL	NWSRFS OPERATION
Unit Hydrograph	Empirical	UNIT-HG
Runoff Models		
Sacramento Soil Moisture Accounting	Conceptual	SAC-SMA
Xinanjiang Soil Moisture Accounting	Conceptual	XIN-SMA
Continuous API*	Empirical	API-CONT
Central Region API Rainfall-Runoff	Empirical	API-MKC
Ohio RFC API Rainfall-Runoff	Empirical	API-CIN
Middle Atlantic RFC API Rainfall-Runoff	Empirical	API-HAR
Colorado RFC API Rainfall-Runoff	Empirical	API-SLC
Baseflow Generation	Empirical	BASEFLOW
Snow Accumulation and Melt	Conceptual	SNOW-17
Routing Models		
Dynamic Wave Routing	Physical	DWOPER
Muskingum Routing	Empirical	MUSKROUT
Tatum Routing	Empirical	TATUM
Lag and K Routing	Empirical	LAG/K
Layered Coefficient Routing	Empirical	LAY/COEF
Channel Loss	Empirical	CHANLOSS
Single Reservoir Simulation	Empirical	RES-SNGL
Rating Curves/Tables		
Stage-Discharge Conversion	Empirical	STAGE-Q

* API stands for antecedent precipitation index

systems to NWSRFS. The NCRFC uses NWSRFS for river and flood forecasting and uses local procedures to issue spring flood outlooks. The MBRFC uses NWSRFS to generate mean areal precipitation and mean areal temperature data sets and uses local procedures for river and flood forecasting and generating spring flood outlooks. There are four major components of the NWSRFS operational forecast system:

1. Data analysis procedures are used to compute mean areal estimates of precipitation, temperature, and potential evaporation from point observations.

2. Modules (referred to as operations) are used to compute and display runoff, river discharges, and stages. These operations include hydrologic and hydraulic models, data manipulation algorithms, and display procedures.

3. Utility programs and databases are required to manage the large volumes of data used by an RFC. In addition to observed data, information on numerous other parameters must be maintained. This parametric information includes rating curves, unit hydrographs, rainfall-runoff curves, channel routing constants, etc. (See below for discussion of these terms.)

4. An operational forecast program command language is required to allow the forecaster to define modeling options, to make adjustments to model state variables (i.e., current state of the river, soil moisture, etc.) and data values, and to recompute forecasts.

Selected models available in the NWSRFS are shown in Table 4-3. The RFCs decide which models are most appropriate to forecast their basins and determine the hydrologic parameters needed in the models. The RFC forecast procedures are normally executed once a day in the morning, after all available precipitation and stage data have been received. Generally, the models simulate hydrologic conditions every 6 hours at synoptic times[1]. During flooding situations, the RFC forecast system is executed at other times during the day as conditions change and new data are received.

4.3.1.1 RUNOFF

Streamflow is an integral part of the hydrologic cycle and is driven by precipitation. Rain that falls can become surface runoff as it travels overland or horizontally through the upper layers of soil to the stream channel; it can sink into the soil and enter the channel as ground water flow; or it can evaporate either directly or indirectly through plant transpiration. Surface runoff is the most significant component for river forecasting. The amount of surface runoff depends on soil moisture content, soil type, terrain slope, and vegetation. The two primary methods of

[1] Synoptic times are 6-hour intervals, starting at 00:00 UTC (Universal Coordinated Time). By convention, hydrometeorological observations are simultaneously made around the globe at these times to allow creation of "synoptic maps" that provide a "snapshot" of the state of the atmosphere at the observation times.

estimating surface runoff use: (1) conceptual models that simulate the physical processes and (2) empirical methods based on time of year, storm duration and intensity, and initial soil moisture content.

Because of the complexity of the physical processes, most current models are "lumped parameter" models. These models assume that a single value can adequately characterize the quantity within the modeled area. For example, an average precipitation value can be used to determine runoff volumes over a small basin. The assumption is that the small spatial and time variations do not adversely affect model computations. For this reason, large basins are usually divided into smaller subbasins.

Conversion of rainfall-runoff to the volume rate of water (discharge) that flows into a stream is commonly done using "unit hydrograph" theory. A unit hydrograph specifies at a particular location the typical time variation of the discharge resulting from 1 inch of runoff averaged over a drainage basin. It assumes that the basin characteristics are homogeneous and that runoff is uniformly distributed over time.

Unit hydrographs may be developed on the basis of observations. Because of limited availability of data and the need to match storm durations with river forecast model time-steps, a different unit hydrograph is needed for each storm duration. The most common unit hydrographs developed and used by the NWS are for 6-hour durations. Figure 4-3 shows an example of a unit hydrograph. RFCs generally develop a unit hydrograph for each basin (and subbasins, if any) in their areas.

Unit hydrograph theory assumes that the discharges generated by runoff amounts other than 1 inch can be produced by using the ratio of computed runoff to the 1-inch storm. As shown in Figure 4-3, a total storm hydrograph results from adding the properly scaled unit hydrograph volumes to base flow. Base flow results from rainfall that infiltrates deeply into the soil and moves laterally within the ground to the stream channel. Because of the retarding effects of flow through the ground, base flow varies slowly and continues long after the rainfall has stopped. As shown in Figure 4-3, during heavy rainfall events, base flow is only a small percentage of the total flow. However, during dry periods, groundwater-driven base flow sustains river levels.

While surface characteristics of a basin, such as soil types (affects infiltration rates), slopes (controls speed of surface runoff), depressions, etc., generally do not vary from storm to storm, soil moisture does. Because soil moisture measurements are not normally available, runoff is adjusted based on estimates or model calculations of soil moisture.

For storms lasting longer than the duration of the standard unit hydrograph (normally 6 hours), successive calculations as described above are made. Each 6-hour interval uses precipitation from previous intervals to adjust soil moisture. The total discharge from a long-duration storm is the summation of hydrographs resulting from the application of the unit hydrograph theory to a series of 6-hour segments that span the total storm duration.

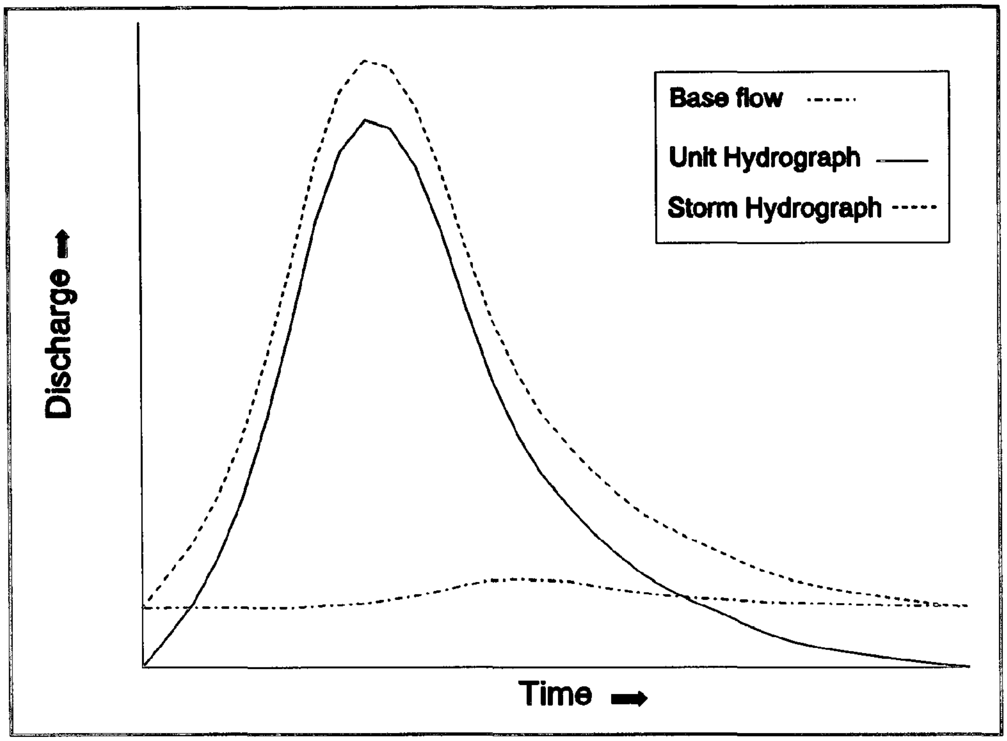


Figure 4-3. *An example of a unit hydrograph, a base flow hydrograph, and the resulting storm hydrograph.*

4.3.1.2 RATING CURVES AND TABLES

While hydrologic modeling is based on flow volumes, most public forecasts are made for river levels or stages. The relation between river stage and flow volume is called a rating curve or a stage-discharge relation. These stage-discharge relations are critical to forecasting the river stages at gaged locations along rivers.

Rating curves are influenced by inertial effects creating unsteady flow (e.g., backwater, water flowing overbank into or out of the main channel, etc.) and by roughness effects (e.g., seasonal changes in vegetative growth, bedform changes, scouring, and sedimentation). When inertial effects become dominant, the relation between stage and discharge can be quite variable. Water within the channel's banks flows faster than overbank flow due to roughness differences.

Roughness effects generally cause rating curves to shift. For example, a given stage will have a larger discharge in early spring when vegetative growth in the channel is minimal than in the summer when heavy growth retards discharge. Also, discharges in rivers heavily laden with sediment, that are continuously scouring and filling, generally produce lower stages during scour.

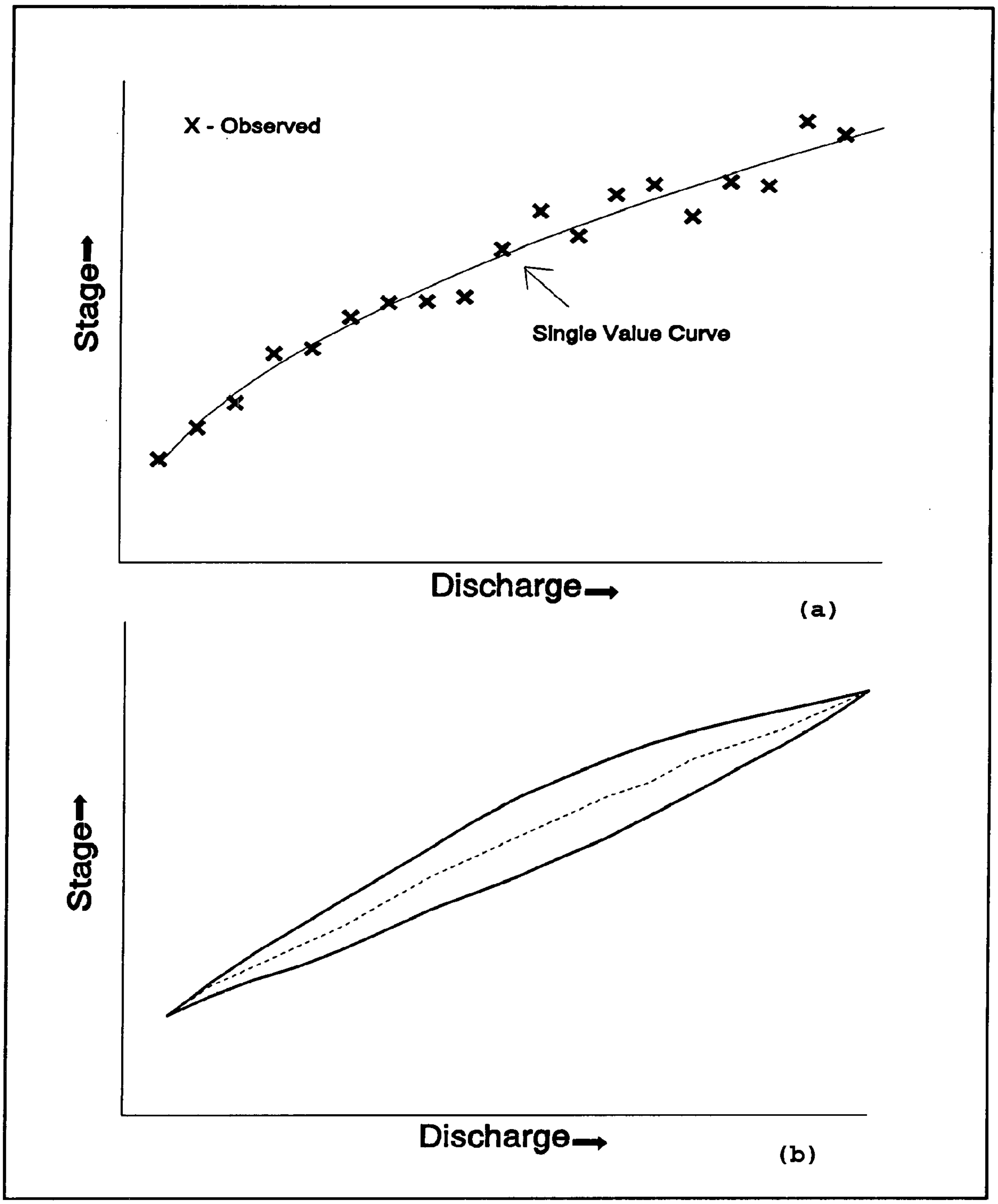


Figure 4-4. *Examples of rating curves: (a) observation points and smooth line representing best estimate of rating curve and (b) loop rating curve.*

Stage-discharge relations are usually developed from a series of field measurements. To measure streamflow, water velocities are measured at a number of locations along a line transversing the river width (cross-section) in the stream using a current meter. The discharge is computed by multiplying segments of the cross-sectional area of the stream channel by the segment average water velocity. A series of measurements are made at many different stages. The measurements are plotted and a smooth line, drawn through the observations, is considered the best estimate of the rating curve. When this information is presented in tabular form, it is called a "rating table." An example of a rating curve, drawn through a typical series of observations, is shown in Figure 4-4(a).

The official rating curve at a gaged location is a single-valued curve which implies a one-to-one relation between stage and discharge. Unfortunately, the discharge associated with a given stage may differ depending on whether the river is rising or falling. For a given stage, the discharge will generally be greater for the rising stage (when the water surface slope is greater than the channel slope) than for the falling stage (when the reverse is true). This effect is particularly pronounced on very mild sloping rivers. Under these conditions, modest changes in stage or current can lead to dramatic differences in discharge. This gives rise to a "looped" rating curve as shown in Figure 4-4(b). The middle curve is intended to represent the single-valued "official" rating curve, while the upper and lower lines show the actual discharge as the river rises and falls. Another reason for lower discharge as the river falls is that the flood crest fills the channel and impedes the flow associated with the falling stages.

The U.S. Geological Survey (USGS) has responsibility for measuring streamflow throughout the United States. The USGS makes discharge measurements and develops most official rating curves used by the NWS. When significant rises occur, the USGS often makes additional discharge measurements and provides this information to the NWS, the COE, and other cooperators. These measurements are used to update rating curves.

4.3.1.3 RIVER ROUTING

As a flood wave travels down a stream that has no intervening tributary flow, the peak flow may be delayed and attenuated. Figure 4-5 schematically shows these effects at three locations along the stream (Location 1 is upstream, Location 3 is downstream). Note that, in this idealized case, the total volume in each hydrograph is constant; as the peak falls, the hydrograph broadens.

While computer models have been developed to simulate the volume and momentum of water as it moves down a stream, the significant amount of information needed to implement such models currently limits their operational use in most cases. Instead, empirical information is used to develop procedures that describe flow from one point along a stream to another. This process is referred to as "storage routing" and relates inflow, outflow, and storage by a "storage function." The determination of the routing constants used in the storage function is based on observations from a range of flow conditions.

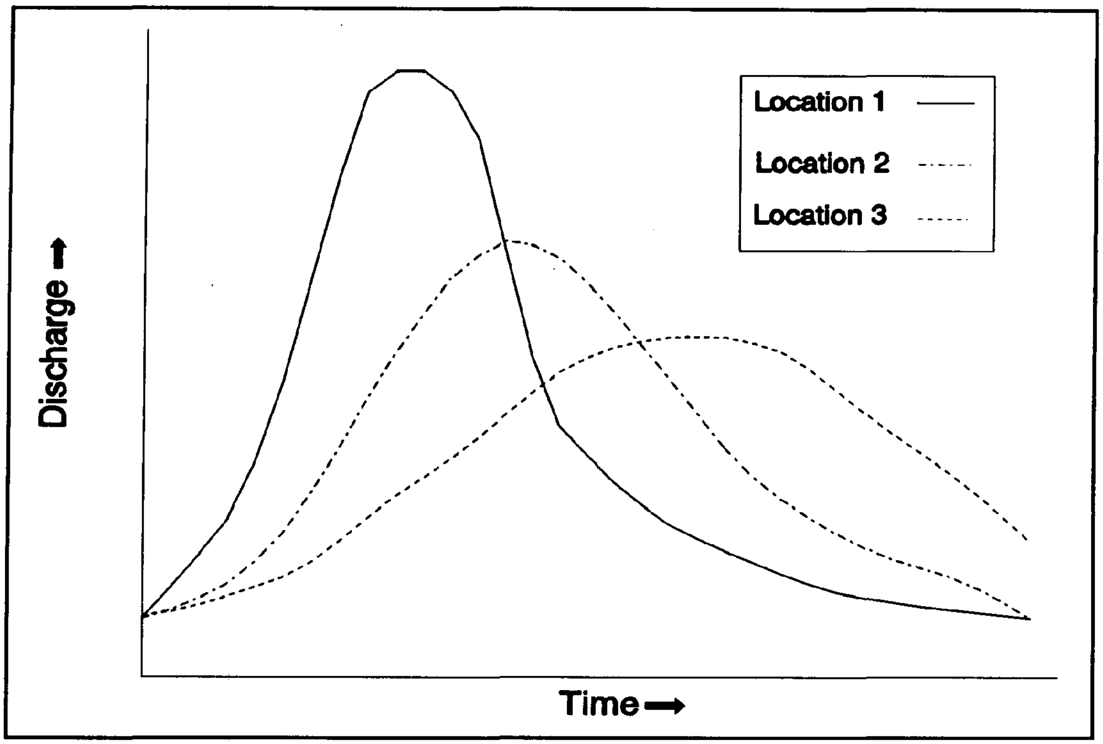


Figure 4-5. *Schematic showing reduction in flood crest as flood wave moves downstream.*

4.3.1.4 RESERVOIR OPERATIONS

When dams and reservoirs exist along a stream, the forecast procedures cannot be applied as described above. Typically, forecasts are made at inflow points for major reservoirs. This information can be used to manage flow through the reservoir. To forecast at points downstream, reservoir releases must be known. The needed information exchange occurs between the NWS and operators of many major reservoirs.

4.4 CURRENT FORECAST METHODOLOGY AT THE NORTH CENTRAL AND MISSOURI BASIN RIVER FORECAST CENTERS

The NCRFC uses the NWSRFS as its operational forecast system. The MBRFC uses the NWSRFS for data analysis and runoff calculations and uses a locally developed forecast system for channel routing, reservoir control, and stage-discharge relations. For runoff, both RFCs use an API model to compute storm runoff using precipitation amounts, an index to antecedent moisture conditions, time of the year, and rainfall duration (API-MKC, see Table 4-3). Mean areal precipitation is computed and runoff calculated on a 6-hourly basis. The storm runoff is converted to discharge using a unit hydrograph. Baseflow amounts are added to the storm runoff hydrograph to get total discharge.

Although the RFCs use different river modeling systems, both rely primarily on the same procedures to route the discharges and obtain river stages. Both RFCs rely on the Tatum routing procedure that is based on storage-routing methodology. River stage is obtained by using the routed discharge and a stage-discharge relation (rating curve), which is generated using observed data. While NCRFC uses a log-log interpolation/extrapolation procedure to manipulate the rating curve (STAGE-Q, Table 4-3), MBRFC uses a linear technique to handle rating curve extensions. Reservoir operations are handled by NCRFC using a procedure that has several schemes and utilities to simulate reservoir conditions (RES-SNGL, Table 4-3). MBRFC uses a technique developed by Goodrich for reservoir operations.

Both RFCs can make various types of adjustments to simulated variables. Runoff volume errors are typically accounted for by changing the volume computed by the runoff model before the unit hydrograph computations. Discrepancies between observed and simulated discharge hydrographs may be handled by blending the two hydrographs together. Rating curves are constantly being adjusted during flood to accommodate the changing hydraulic conditions in the river. Currently, these adjustments are accomplished manually.

4.5 WEATHER SERVICE OFFICES WITH HYDROLOGIC RESPONSIBILITIES

While hydrologic guidance is provided by the RFCs, hydrologic forecasts based on this information are issued to the public by selected NWS offices (generally WSFOs) having hydrologic service area (HSA) responsibilities. See Figure 4-6 for HSA areas of responsibility.

HSA offices currently have very limited forecasting tools. Most RFCs provide their HSA offices with headwater tables. These tables provide estimates of the flood peak for any specified amount of precipitation and an index that characterizes soil moisture conditions. These tables can be used on selected basins to generate preliminary forecast crests on fast-responding streams before the RFC hydrologic forecast is provided to the HSA offices. Although some HSA offices have simple crest-stage forecast techniques, there are no sophisticated hydrologic procedures for routing flow or for handling complex systems.

HSA offices provide the RFCs with information used in the river forecast system. This includes observations of precipitation and river levels. HSA offices also provide other key hydrologic information including gage locations, historical flood (and low-water) records, impacts of floods at various levels, etc. Much of this information comes from other agencies and is summarized on a standard NWS form E-19. The HSA office is responsible for keeping the E-19s current. Much of the E-19 information must be updated as a result of the altered conditions produced by The Great Flood of 1993.

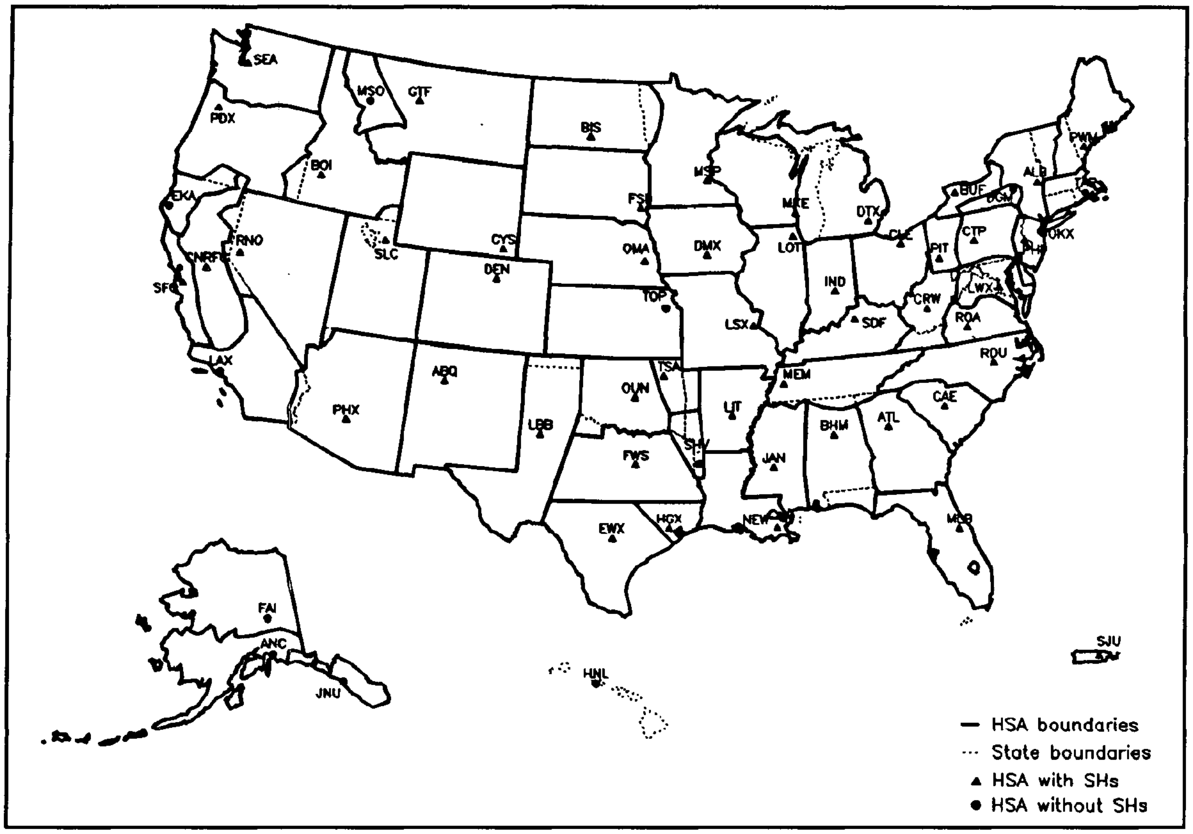


Figure 4-6. *Locations of, and areas served by, the NWS offices with Hydrologic Service Area responsibilities.*

FINDING 4.1: Accurate river gage and other information reported on NWS Form E-19 is critical to hydrologic forecast techniques and procedures. The severe flooding of both the Mississippi and Missouri Rivers and their tributaries will necessitate updating much existing E-19 information.	**RECOMMENDATION 4.1:** The Regional Hydrologist, Area Managers, Hydrologists in Charge, and Service Hydrologists should coordinate with the COE, USGS, and other agencies to research, verify, and update river stage levels and other information required by Form E-19 at all affected reporting points.

4.6 FORECASTING CHALLENGES DURING THE GREAT FLOOD OF 1993

The Great Flood of 1993 presented many challenges to NWS river forecasters. The following sections highlight limitations in the current data and procedures used by the NWS.

4.6.1 DATA INPUT

Precipitation is one of the most important input quantities to any hydrologic forecast system. To date, precipitation observations are obtained from point sources or rain gages. The area of a representative runoff zone (i.e., subbasin) forecast by NCRFC and MBRFC is 300-500 square miles. Typically, an average of 3-5 rain gages are used to represent the amount of precipitation over that area. Because of the comparatively few rain gages, heavy precipitation areas can be missed (especially in convective thunderstorm patterns that occurred during The Great Flood of 1993).

Another important consideration is the lag between times when precipitation occurs and when it is available to the forecast system. Forecast preparation at the NCRFC and MBRFC is closely tied to precipitation measurements made by the cooperative network at 12:00 UTC every morning (7 a.m. CDT). These measurements represent a 24-hour period between 12:00 UTC the previous day and 12:00 UTC for the current morning. It is at this time when forecast models have the maximum amount of precipitation data available. Forecast models can be executed at other times during the 24-hour period, usually on synoptic 6-hour periods; but precipitation observations for these periods are far fewer. Taking observations in the cooperative network is a manual process, requiring a person to take and transmit an observation. Remote Observation System Automation (ROSA--see Section 5.2.1) has helped in transmitting these data and in reducing manual intervention but not in improving the frequency at which observations are taken. Observations made more than once a day (12:00 UTC) currently are very limited over much of the area affected by The Great Flood of 1993. This hinders the forecasters' ability to use the forecast system to prepare updated forecasts.

The NCRFC and MBRFC can also receive precipitation data from automated data collection platform (DCP) sites (see Section 5.2.2.1). These automated sites are equipped with "tipping bucket" rain gages and transmit precipitation data often accompanied by river stage data. Both RFCs indicated that rainfall data received from tipping buckets were suspect and difficult to use.

River stage observations are also very important input to the forecast system. Many river stage locations are now automated (e.g., DCPs) and provide more timely data. Some DCPs, however, are still not programmed to transmit randomly, or on significant events (see Section 5.2.2.1).

4.6.2 RATING CURVES

Changes in the river bed caused by sedimentation and scouring, backwater conditions[2] along tributaries, and locally stored water in inactive floodplain areas may result in the continuous shifting of the rating curves.

Rating curves play an important part in the forecast methodology used by NCRFC and MBRFC. The NWS river forecast system routes volumes of water to locations downstream. These discharges are converted to river stages using rating curves. RFC forecasters can also use stage measurements to estimate discharge as an aid in evaluating volumes predicted by the models. The official rating curve at a gaged location (based on USGS measurements) is a single-valued function that describes a one-to-one relationship between stages and discharges. Unfortunately, in many cases, the relationship between stages and discharges is not one-to-one. Generally, the relationship on very mild sloping rivers shows a looping effect where, for a given flow, the stage on the rising limb of the hydrograph may be different from the stage on the recession side (see Figure 4-4(b)).

Any extension of a rating beyond measured flow values can result in inaccurate stage-discharge relationships. The NCRFC and MBRFC use log-log and linear extrapolations, respectively, to extend rating curves. Neither of these techniques take into account the channel conditions (e.g, cross-sectional geometry, roughness, etc.) and, if used without adjustment, would probably overestimate the stage. A more appropriate way to extend the rating curves would be to apply a hydraulic extension procedure. Both a hydraulic extension and a loop rating option are being developed for the procedure that relates stage to discharge (STAGE-Q) in NWSRFS.

During The Great Flood of 1993, rating curves underwent continuous, manual adjustments that were primarily based on special or emergency stage-discharge measurements and the hydrologists' experience and intuition. At times the hydrologists felt as though they were forecasting rating curves instead of stages.

<u>FINDING 4.2:</u> The number of sites where backwater or loops in ratings affected forecasts was unprecedented.	<u>RECOMMENDATION 4.2:</u> Loop rating curves are an indication that a dynamic wave routing technique is required. Each RFC and the Office of Hydrology should investigate the input data, model calibration, and simulation results associated with implementation of a dynamic wave model in any affected area.

[2] Backwater effects result from a downstream build up that prevents normal flow of water. A common situation leading to the backwater phenomena occurs when a main stem stream experiences high stages. In the vicinity of tributaries that flow into the main channel, the water level in the main channel can be higher than stages of the tributaries. This results in flow out of the main channel into the tributaries. The flow is in the opposite direction to normal flow on the tributaries, resulting in a backwater effect.

<u>FINDING 4.3:</u> In many of the flooded areas on the Missouri and Mississippi Rivers, the stages exceeded those of prior records while the corresponding volumes of flow often did not. Assessment of the causes of this factor are important to the objective of applying the best river hydraulics in future river modeling and forecasting.	<u>RECOMMENDATION 4.3:</u> In The Great Flood of 1993, levee effects and unknown ratings are probably the dominant causes of discrepancies between the river stages and volumes of flow. The Hydrologic Research Laboratory should use the dynamic wave model to determine the causes for these discrepancies. Additionally, new ratings must be established for many forecast points.

4.6.3 FLOOD ROUTING

The Great Flood of 1993 encompassed many hydraulic conditions that made the operational routing procedure inadequate. Backwater effects were a serious problem throughout the flooded area. These effects were due to a multitude of reasons including channel constrictions (e.g., since the levees held around the city of St. Louis along the Mississippi River, the water converged there and caused backwater effects upstream); inflows from large tributaries (e.g., the confluence of the Missouri and Mississippi Rivers); and off-channel storage of water trapped behind levees. Levee overtopping and failures (discussed in Section 4.6.5) made it very difficult to account for the volume of water (discharge) in the system. Sedimentation (which causes changes in the channel geometry) in the Missouri River also made forecasting of river stages difficult. Storage routing models are not able to handle situations where flows were subject to such complex hydraulic conditions.

4.6.4 RESERVOIR EFFECTS

Numerous, multipurpose reservoirs maintained by the COE and several Bureau of Reclamation reservoirs were highly effective in reducing stages during The Great Flood of 1993. The magnitude of the reductions depended on many factors including location of storms and reservoirs, available reservoir storage, type of reservoir, and intervening local area between damage center and reservoir. Although the actual stage reductions have not been finalized, the volume of water stored in many midwestern reservoirs during The Great Flood of 1993 set records.

Flood control operations at projects in the Missouri and Mississippi River basins helped regulate the contributions by those basins to the Mississippi River at St. Louis and downstream. Missouri River main stem and tributary projects also significantly reduced stages along the Missouri River itself. Other projects closer to damage centers provided reductions at key levees and other critical locations. With approved deviations from standard operating procedures, many projects were regulated to further reduce downstream stages.

Detailed analyses of the effectiveness of these flood control operations is beyond the scope of this survey report and generally falls to the agency directly responsible for facility operations. For example, the COE plans to publish a post-flood report in approximately 4-6 months detailing project operations, downstream stage reductions, and resulting benefits of COE projects. The effectiveness of the NWS forecast and warning service and the associated coordination between the NWS and water control facility operators is, however, an important part of this survey.

The COE uses NWS river forecasts to plan the regulation of their reservoirs. In some instances, contingency forecasts were made by the NWS for the COE based on quantitative precipitation forecasts (QPF) (see Sections 5.2.4.2 and Appendix B). At present, NWS forecasts at both the NCRFC and MBRFC do not normally use QPF directly to account for future rainfall. Upon request from the COE, forecasts were run at the MBRFC with bands of 1 or 2 inches of potential rainfall so that the COE could look at alternative reservoir operations.

4.6.5 LEVEE EFFECTS

The Great Flood of 1993 was influenced (and to some extent, caused) by more than 1,500 levees throughout the Mississippi and Missouri River basins. While the effects of specific levees and their failures during the flood can be argued, general effects can be briefly discussed.

As water leaves the channel and flows into the overbank (floodplain) areas on the rising limb of the hydrograph, levees prohibit floodplain storage. This concentrates greater volume in the higher velocity channel segment and produces a higher peak discharge downstream since the flow cannot be stored in the overbank area protected by the levees. At the same time, however, levees restrict the amount of flow passing a point on the river, thus tending to increase the velocity and deepen the channel.

Again, depending on location and configuration, a levee breach could occur and make significant storage suddenly available. The breached levee could "regulate" flow by rapidly removing water from the channel and reducing downstream discharges. The magnitude of this effect obviously depends on many factors. Some of these include the levee elevations and breach widths, the height of the water level (head) over the breach, and the storage volume available behind the levee.

All of these effects occurred, to some degree, along the lower Missouri and upper Mississippi Rivers during this record event. Other effects occurred, including multiple breaches of levees, that dramatically decreased the flow in the river by forming high-flow relief channels in the floodplain behind the levees. This significantly reduced both upstream and downstream flood heights.

When levee breaches occurred, RFC forecasters generally assumed that water flowing into areas behind the levees would only temporarily reduce the discharge on the rising limb of the flood hydrograph. As the area behind the levees filled, the effect of the breaches on river stages decreased. This was followed by water returning to the channel once the flood peak had passed.

To better define the specific effects of levees and their breaches during this flood, it is necessary to use dynamic routing models that account for unsteady flow effects, levee breaching, flow conveyance on the floodplains behind breached levees, and floodplain storage. Such models use the continuity and momentum equations and account for both the conveying (carrying) capacity and the available storage of the floodplain (see Section 4.7.2). Two major, undefinable factors during this flood were: (1) the location and size of levee breaches, particularly before the failure occurred, and (2) the ability to quantify the available storage behind the levees and the amount of return flow over time.

FINDING 4.4: Levee effects on overbank storage and downstream forecasts were difficult to analyze. The size and type of failures were highly variable.	RECOMMENDATION 4.4: The use of airborne photographic reconnaissance to pinpoint levee failures should be an option readily available to RFCs. The Hydrologic Research Laboratory and the RFCs should investigate more effective ways to model levees and levee failures.
FINDING 4.5: St. Louis District COE has profiles of Federal levees with top-of-levee elevations for non-Federal levees. Some levee profiles may change in the aftermath of the extensive flooding.	RECOMMENDATION 4.5: The NWS should coordinate with the COE to obtain levee information for use in forecast procedures, especially when implementing the dynamic wave model in areas affected by the flood.

4.6.6 USER INTERACTION WITH FORECAST SYSTEM

Currently, river forecasts are typically made on a mainframe computer at the NOAA Central Computer Facility (NCCF) in Suitland, Maryland. Input information is prepared at each RFC and submitted via phone lines for batch processing at the NCCF. Once the batch job is executed, model output is returned via phone lines to the RFCs.

```
ST LOUIS MO         - MISSISSIPPI R            NOV 1993  CST      EADM7            *** ENGLISH UNITS ***

    O = EADM7     QIN  (CFS )    F = FLOOD STAGE                            NWS-ID =      EADM7
    * = EADM7     QINE (CFS )    U = RATING UPPER LIMIT                     DATUM  =      379.94
    + = EADM7     SQIN (CFS )    M = MAX OF RECORD
    A = ALNRTD    SQIN (CFS )
    M = MOCONRTD  SQIN (CFS )

    FLOOD STAGE   =   30.0       FLOOD FLOW     =  497599.9        MAX OF RECORD  STAGE = 43.2
    WARNING STAGE = -999.0       BANKFULL STAGE =   -9999.9                       FLOW  =1300000.0
    PLOT STAGE    =   30.0       FCST CRITERIA  = DAMA      SOOP                  DATE  =  4-28-1973

COMMENTS:  RATING INPUT ON 7-25-93... PN

                  STAGE-7.0    2.7       12.7      19.5      25.0     30.1
DA HR SSTG EADM7G EADM7.000 100000.0  200000.0  300000.0  400000.0  500000.0   ADJQ(*)  SIMQ(+)   RO  ROQ
BF( 868.)
11 18   13.9  13.67   0.00 I    MIA        +*        I         I      FI 215367.  209377.  0.00     0.  1.
12  6   13.8  13.39  13.85 I    MIA        +O        I         I      FI 215353.  207691.  0.00     0.  1.
12 18   13.8  13.78   0.00 I    MIA        I*        I         I      FI 214239.  210671.  0.00     0.  1.
13  6   13.7  13.72  13.72 I    MIA        IO        I         I      FI 213660.  214306.  0.00     0.  1.
13 18   13.9  13.83   0.00 I     MA        I*        I         I      FI 216012.  215126.  0.00     0.  1.
14  6   15.4  15.16  15.44 I     MA        I  O      I         I      FI 235860.  233236.  0.30  2850.  1.
14 18   18.7  18.59  18.75 I     I A       I     + O I         I      FI 288255.  263003.  0.28  5960.  1.
15  6   20.8  20.81  20.85 I     I   AM    I       + I O       I      FI 324134.  287640.  0.00  5330.  1.
15 18   22.8  22.84  22.84 I     I    AM   I         +    O    I      FI 359921.  304312.  0.00  4500.  1.
16  6   23.2  23.27  23.25 I     I   A M   I         I+    O   I      FI 367353.  318102.  0.00  4190.  1.
16 18   22.8  22.62   0.00 I     I  A   M  I         I +  *    I      FI 358633.  324443.  0.01  3415.  1.
17  6   22.4  22.38  22.39 I     I  A    M I         I  + O    I      FI 351786.  333151.  0.10  3510.  1.
17 18   23.8  23.39   0.00 I     I  A      M         I   +  *  I      FI 376510.  346430.  0.01  2850.  1.
18  6   25.3  25.35  25.35 I-----I---A-----IM--------I-----+---O------FI 405780.  363044.  0.00  1800.  1.
18 18   26.3   0.00   0.00 I     I    A    I M       I       +  I *    FI 424007.  381804.  0.00  1220.  1.
19  6   27.0   0.00   0.00 I     I    A    I  M      I        +I  *   FI 437214.  395546.  0.00   780.  1.
19 18   27.1   0.00   0.00 I     I    A    I   M     I        +I  *   FI 437955.  396821.  0.00   600.  1.
20  6   26.2   0.00   0.00 I     I   A     I  M      I       +  I *    FI 422093.  381493.  0.00   420.  1.
20 18   24.7   0.00   0.00 I     I  A      IM        I    +   *I      FI 394645.  354579.  0.00   245.  1.
21  6   23.0   0.00   0.00 I     I A      MI         I +   *   I      FI 363597.  324065.  0.00   120.  1.
21 18   21.5   0.00   0.00 I     I A    M  I        +I  *      I      FI 335538.  296541.  0.00    10.  1.
22  6   20.2   0.00   0.00 I     IA   M    I      +  I*        I      FI 311878.  273415.  0.00     0.  1.
22 18   19.0   0.00   0.00 I     IA M      I    +   *I         I      FI 292420.  254491.  0.00     0.  1.
23  6   18.1   0.00   0.00 I     IAM       I  +   *  I         I      FI 276974.  239580.  0.00     0.  1.
23 18   17.4   0.00   0.00 I     IA        I +   *   I         I      FI 265668.  228808.  0.00     0.  1.
24  6   16.9   0.00   0.00 I     MA        I +  *    I         I      FI 257872.  221546.  0.00     0.  1.
24 18   16.6   0.00   0.00 I     MA        I+   *    I         I      FI 252457.  216665.  0.00     0.  1.
25  6   16.4   0.00   0.00 I    MIA        I+  *     I         I      FI 248801.  213543.  0.00     0.  1.
25 18   16.2   0.00   0.00 I    MIA        I+  *     I         I      FI 246384.  211661.  0.00     0.  1.
26  6   16.1   0.00   0.00 I    MIA        I+  *     I         I      FI 244636.  210447.  0.00     0.  1.
```

Figure 4-7. *Example of current NWSRFS batch output available at RFCs.*

A forecaster must examine forecast output on large amounts of printer paper or, in the case in the NCRFC, on a monitor (CRT). An example of the type of output provided for a single location is shown in Figure 4-7. This output format typically does not show enough detail or other information that would be useful to the forecaster. The forecaster may have to flip line-printer output (or CRT screen images) "back-and-forth" to examine upstream basins that may affect the downstream forecasts.

If the forecaster determines that data-input or model variables need to be altered, it can be a cumbersome and time-consuming process to resubmit the job to the NCCF, wait for the results, and work through a second pile of line-printer output. Additionally, the current mainframe, batch-oriented technology supported by the NCCF and used to make operational hydrologic forecasts at the MBRFC and the NCRFC does not facilitate real-time interaction between forecasters. The ability of forecasters to review visually the graphic, hydrometeorologic data sets between RFCs would have dramatically facilitated inter-RFC communications.

FINDING 4.6: Coordination between the MBRFC and NCRFC for the Missouri River forecast at Hermann, Missouri, was critical. Attempts to coordinate over the telephone were somewhat successful, but much of the information exchange was hampered by technological limitations. Limitations in the current RFC technology do not allow the Hermann forecaster at the MBRFC and the St. Louis forecaster at the NCRFC simultaneously to view all of the graphic and hydrologic information (including WSR-88D, hydrograph, satellite, and derived data sets) used by the other forecaster as input to his/her forecast procedures.	RECOMMENDATION 4.6: The NWS should aggressively pursue installation of modernized facilities at RFCs (see Recommendation 4.10, 5.15, and 5.16) required to support the NWSRFS, the Interactive Forecast System, and inter-RFC communications.

4.7 MODERNIZED RFC/WSFO HYDROLOGIC FORECAST METHODOLOGY

The forecast methodology in the modernized NWS at both the RFCs and WSFOs will change dramatically (see Chapter 2). Changes will occur in all functions of the River Forecast System shown in Figure 2-1.

4.7.1 INPUT

One of the most significant changes will be in the way precipitation observations are processed and used in the forecast system. Point precipitation observations will be merged and processed with precipitation estimates from multiple Weather Surveillance Radar 88 Doppler (WSR-88D) radars and information received from satellite observations. The result will be frequently updated, multisensor, high-resolution precipitation estimates. It is anticipated that RFCs will have these high resolution data sets for their entire areas of responsibility. The availability and use of these data sets will change the way hydrologists interact with and use hydrologic forecast models. Many of the problems associated with having only "point-source" precipitation data will be reduced or eliminated. Forecasters will change their "mind-set" from executing forecast systems based on 12:00 UTC, or at 6-hourly intervals, to running interactively the model in near real-time as estimates of precipitation fields change hourly or even more frequently. RFCs will also have access to gridded QPF estimates for use in their forecast systems.

4.7.2 MODELING

After modernization and associated restructuring (MAR) of the NWS is complete, RFC Advanced Weather Interactive Processing Systems (AWIPS) will have sufficient computing power to run NWSRFS locally. RFCs will be able to run NWSRFS with time steps smaller than the 6-hour intervals currently used. This will allow effective integration of WSR-88D rainfall estimates. With MAR, NWSRFS will run in an interactive mode, allowing RFC hydrologists to easily change input to the hydrologic models and make river and flood forecasts in a more timely manner.

High-resolution precipitation data will allow the hydrologist to reexamine how models are implemented. Rainfall/runoff models and runoff distribution models (e.g., unit hydrographs) will eventually change from "lumped parameter" models to distributed parameter models based on gridded data. This will be a gradual evolution, nevertheless feasible due to the eventual availability of gridded precipitation estimates.

A major challenge along the way to implementing distributed, physically based hydrologic/hydraulic models that take maximum advantage of the new observation systems (e.g., WSR-88D radars) is the massive amount of time and effort needed to assemble the information required to calibrate these models. The complex spatial variations across the soil surface and within the soil zone are integral to the solution of the hydrologic modeling problem. It is imperative that resources be found to accomplish the transition from statistical/empirical modeling to modeling the relevant physical processes. Otherwise, the quantum leap in observation systems, communications links, and computer power provided by MAR will never be fully realized by the NWS hydrology program.

The **D**ynamic **W**ave **OPER**ational (DWOPER) model is a physically based, distributed, hydraulic routing model that simulates flow along a river using equations describing mass continuity and momentum of the water for unsteady flow. It allows the flow rate, velocity, and water level to be computed as functions of time and distance along the river, rather than time alone as in the hydrologic method. Calibration[3] of the model requires a large amount of

---

[3] Almost all models, whether empirical or physically based, are not able to account fully for all aspects of the phenomena being modeled. This comes about either because we do not completely understand all the relevant physical processes or, if known, adequate mathematical representation cannot be found. In addition, the mathematical representation of the processes may be so complex that current computational capabilities may not be adequate to make the needed calculations. Finally, data needed to adequately define the starting conditions to be modeled are often not available. Because of these problems, most models can only approximate the phenomena being modeled. The process of applying a model to real data and adjusting the difference between the prediction and actual observations by modifying model parameters is called calibration. Depending on the sophistication of the model, calibration can be a difficult process.

historical data, including stages, discharges, and cross-sectional geometry. Roughness coefficients are obtained in the calibration process. Additional capabilities that are unique to the dynamic wave method include: routing flows through hydraulic structures, such as bridges and dams (including breaches); routing water over floodplains, levee overtopping, and failure (including storage or flow of water behind levees); backwater effects due to channel constrictions, dams, bridges, tributary inflow, mildly sloping river beds, and tides; off-channel storage of water due to ponding; and flow diversions. Implementation of the DWOPER model on portions of the river systems affected by The Great Flood of 1993 would enhance NWS forecasting capabilities.

Since the DWOPER model in NWSRFS computes water levels and discharges simultaneously at every location along the rivers in the system for each time step, the rating curves generated include all of the hydraulic effects that are incorporated in the model. Although DWOPER is capable of simulating rating curves beyond the period of record and at ungaged locations, the forecaster must exercise judgment when using the results.

The DWOPER model has levee capabilities; however, it is not currently designed to forecast levee failures in real-time or on rivers with levee systems as extensive as those on the Mississippi and Missouri Rivers. The levee option in DWOPER is being enhanced to improve its forecast capabilities. These enhancements include storage routing in the floodplain once a levee has been overtopped or failed and adding run-time modifications to allow the breaching characteristics to be changed in real-time.

The accurate calibration of the NWSRFS hydrologic/hydraulic models, including DWOPER, is critical to their effective use in hydrologic forecasting. Many of the procedures use spatial data sets for calibration and implementation. The advanced techniques and procedures provided by Geographic Information Systems (GIS) make available valuable tools that can be used in the hydrologic model calibration and implementation process.

<u>FINDING 4.7:</u> Portions of the Mississippi and Missouri River basins have many complex hydrologic and hydraulic elements that require application of advanced modeling approaches to handle such effects as backwater at river junctures, overbank flows, levee failures, and changing ratings.	<u>RECOMMENDATION 4.7:</u> The RFCs and the Office of Hydrology should accelerate the implementation of the dynamic wave routing model on those river reaches where its capabilities are required.

FINDING 4.8: Detailed GIS systems would have helped in the design and calibration of some hydrometeorological procedures, as well as allowing for more site-specific delineation of flood occurrences.	**RECOMMENDATION 4.8:** NWS Headquarters should carefully examine plans for use of GIS applications within the AWIPS program to assure the most effective use of this technology to assist the national hydrology program.

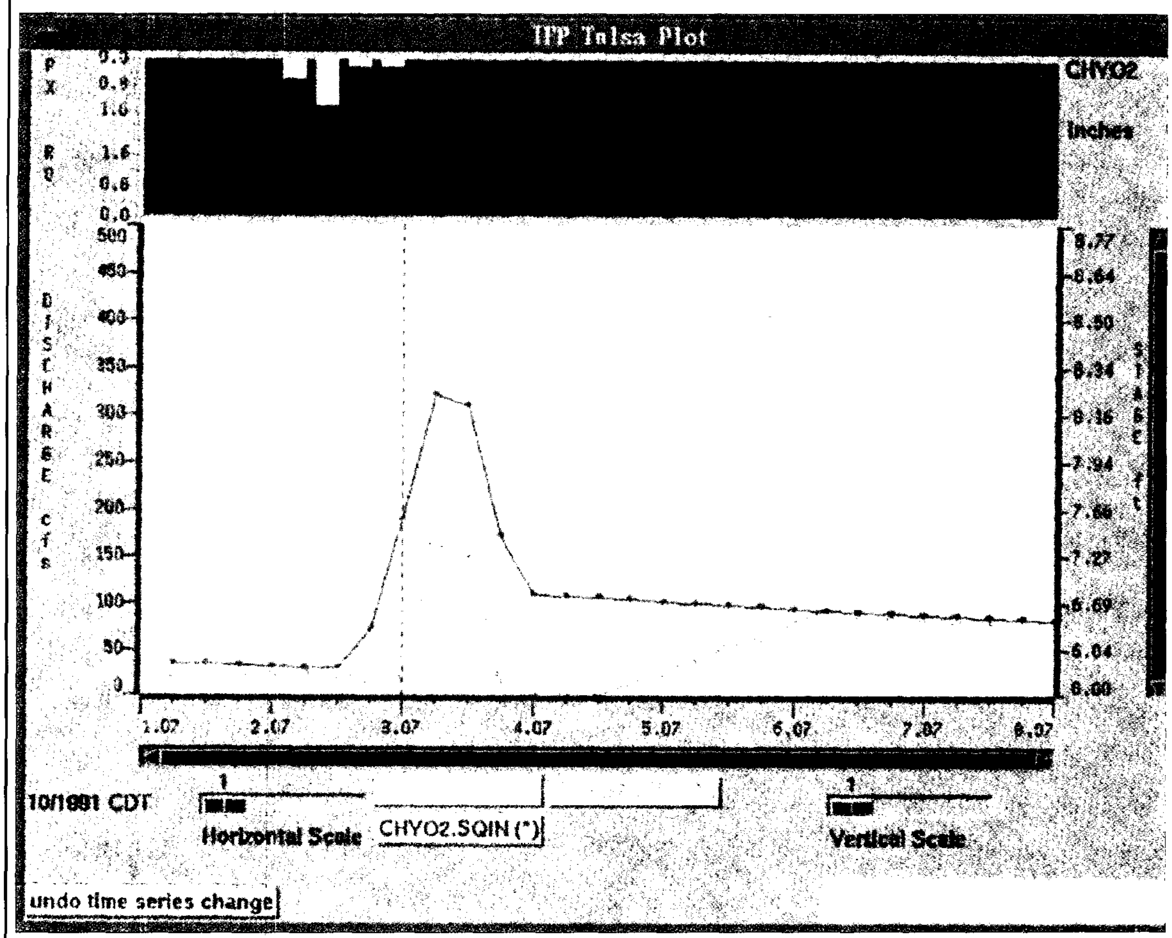


Figure 4-8. *Example of modernized forecast system output that will become available at RFCs in the future.*

4.7.3 HUMAN INTERACTION WITH THE FORECAST SYSTEM

The way a forecaster interacts with the forecast system will also be changed dramatically with MAR. Forecasters will be able to interact easily and quickly with the forecast system. The forecast system will run on local workstations using a local database management system to handle observations and parametric data. Forecasters will interact with the system using interactive "point-and-click" technology in a windowed environment. If changes are needed in data input or adjustments needed to model variables, they can be made easily with an on-line, interactive forecast system. During rapidly changing hydrometeorological events (e.g., heavy precipitation events, dam breaks, or levee failures), forecasters will be able to interact quickly with the forecast system and to produce updated forecasts. Output will be graphical and provide much greater detail and more information than is currently available, as shown in Figure 4-8 (compare with Figure 4-7). A pictorial view of modernized RFC hydrometeorological operations is shown in Figure 2-6.

Another major change will occur at the Weather Forecast Office (WFO). These offices will have on-site, local processing enabling them to produce and update forecasts for most headwaters in their areas. Hydrologists and meteorologists at the WFO will be able to interact with the local hydrologic models using point-and-click technology. They will be able easily to view and to use the latest forecasts received from the RFCs and to disseminate these forecasts to their users.

In summary, the hydrologic forecast methodology will change in many ways in the modernized RFC and WFO. High-resolution precipitation data, the use of QPF, the change to distributed hydrologic/hydraulic models, and the use of an interactive forecast system will greatly improve the way that hydrologic forecasts are made. Forecasters will have much more spatial information, e.g., inundated floodplain areas along rivers, rather than a single water elevation that currently represents the flooding situation along many miles of the river. In addition, the forecaster will be able to convey far more information to the end-user. Forecasts with explicit probabilities, or confidence bands, will convey to the end-user the confidence, or level of certainty, that the forecaster has in any specific forecast. In this way, the modernized hydrologic forecast methodology will provide not only the forecaster with a mechanism to impart more hydrologic forecast information to the end-user but also will provide more information to the end-user to construct a risk analysis for alternative hydrologic scenarios.

<u>FINDING 4.9:</u> Current limitations in operational implementation of hydrologic/hydraulic models, computer hardware, and software contributed to the inability of the RFCs to incorporate QPF amounts into river forecasts on an objective, routine basis.	<u>RECOMMENDATION 4.9:</u> The RFCs should move as quickly as possible to implement advanced hydrologic/hydraulic models and planned, modernized methods to objectively and routinely incorporate QPFs. Since these planned methods require AWIPS-type technology, the RFCs should also investigate ways in which QPFs may be objectively incorporated into the river forecasts in the near term (see Finding 2.10 above) without damaging the integrity of the forecast (e.g., issuing a banded forecast based on potential rainfall).
<u>FINDING 4.10:</u> The forecasters and end-users expressed frustration with the limited amount of information contained in the river forecasts. Sufficient information is not provided to do a proper risk analysis. Forecasters compute total hydrographs and have some feel for the potential effects of various hydrologic contingencies, such as levee failures and rating shifts. There is currently no way routinely to convey this additional information to the sophisticated end-users capable of benefiting from the added information.	<u>RECOMMENDATION 4.10:</u> As soon as possible, the NWS should: (1) install AWIPS and AWIPS-type equipment at the RFCs (see Recommendation 4.6, 5.15, and 5.16) and (2) implement the Water Resources Forecasting System (known as WARFS) to provide the required hydrologic forecast capabilities (see Recommendation 2.9).

CHAPTER 5

DATA ACQUISITION, TELECOMMUNICATIONS, FACILITIES, AND COMPUTER SYSTEMS

5.1 INTRODUCTION

This chapter describes the data acquisition systems used by the National Weather Service (NWS) and their performance throughout the flooded area. It also outlines the status of the facilities, telecommunications networks, and computer systems used by NWS offices.

Maintaining reliable precipitation and river stage data was a major problem affecting forecast operations in the flooded area. NWS offices unanimously expressed the desire to increase the number of stream and precipitation gages in their areas. There has been a continuing decline in both the number of these gages and the resources available to maintain them. Although the offices often had access to data from non-NWS acquisition systems, the data were often in different formats requiring manual manipulation of the data. The posting, data management, and quality control of hydrometeorological data, in general, was slow, laborious, nonsystematic, and incomplete.

The magnitude of the flood demonstrated the dependence of NWS River Forecast Centers (RFC) on a number of electronics systems. Many of these systems are based on obsolete computer and communication architectures and required considerable support and maintenance to keep them operational.

Section 5.2 describes the primary data acquisition systems used by NWS offices in the flooded area and their performance during the flood event. Sections 5.3 and 5.4, respectively, review the status of telecommunications services and facilities used by the NWS. Sections 5.5 and 5.6 contrast the current RFC and Weather Service Forecast Office (WSFO) computing capabilities with those that will be available in the modernized NWS and supported by Advanced Weather Interactive Processing System (AWIPS) and other advanced technologies.

FINDING 5.1: Most NWS offices indicated that a shortage of stream and precipitation gages hindered their ability to produce accurate and timely forecasts. The Des Moines case study in Chapter 6 dramatically illustrates the major impact that the loss of just one stream gage can have on hydrologic forecast procedures.	RECOMMENDATION 5.1: NWS field offices should continue to provide support to cooperating agencies in their efforts to obtain resources for the maintenance of existing gages and the installation of additional stream and precipitation gages in strategic locations.

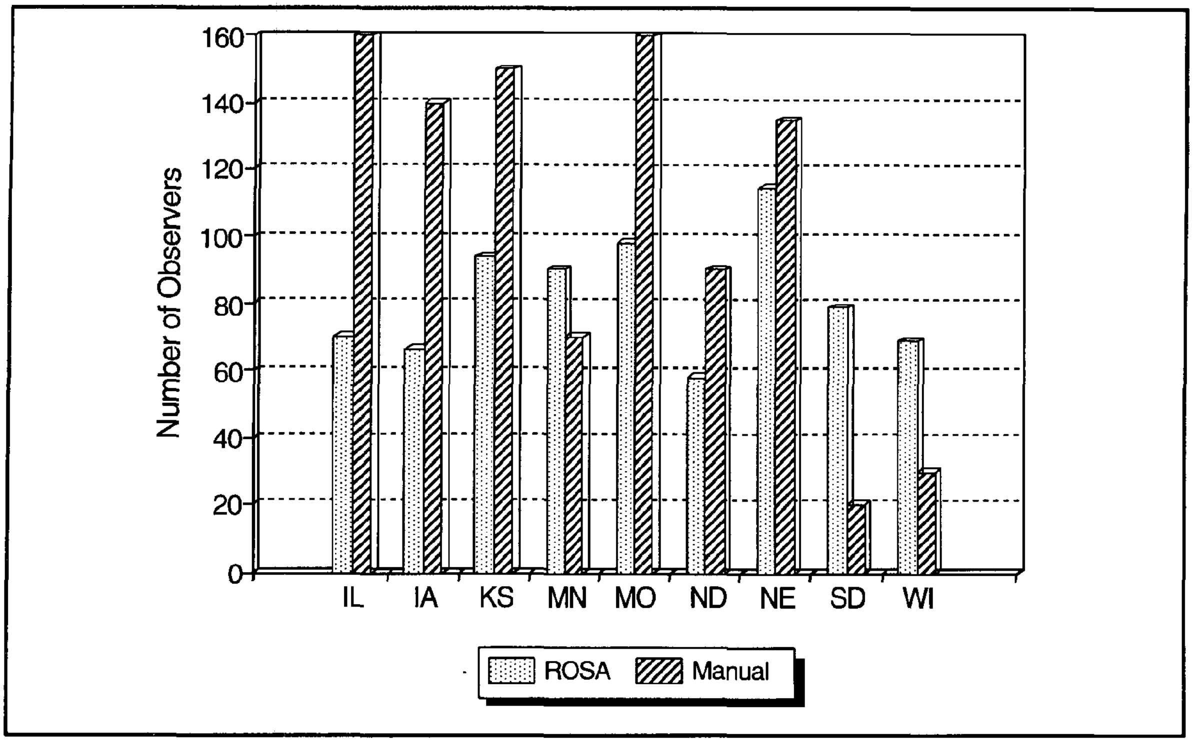


Figure 5-1. *Distribution of cooperative observers, by state.*

5.2 DATA ACQUISITION

5.2.1 COOPERATIVE OBSERVER NETWORK

The NWS Cooperative Observer Network provides hydrometeorological data to NWS offices at higher spatial resolutions than would be available using only standard surface observations. The network in the affected area consists of about 1,700 observers; their distribution, by state, is summarized in Figure 5-1. Data collected by the cooperative observers are used by RFCs as input into their river forecast models, by WSFOs in producing summaries of hydrometeorological conditions for their forecast areas, and by various other agencies in determining local climatology.

Cooperative observers manually collect data such as precipitation, river stage, snowfall, and maximum and minimum temperatures. Observed data are routinely reported to the local WSFO or Weather Service Office (WSO) each morning. Some observers provide additional precipitation measurements during times of significant rainfall based on prescribed criteria. Approximately 45 percent of the cooperative observers in the Central Region transmit their data to NWS offices using a system called Remote Observation System Automation (ROSA). ROSA is a telephone keypad data entry system that allows cooperative observers to enter their reports automatically into a central ROSA computer. These data are then automatically coded in Standard Hydrometeorological Exchange Format (SHEF) and routed to RFCs and used as input to their computer models.

Other observers who are not in the ROSA program must telephone their reports to an NWS employee who, in turn, must manually encode the observations in SHEF and transmit them through the Automation of Field Operations and Services (AFOS) system, the current NWS operational communications network. Coding errors occurred as a consequence of significant operational stress and because some of those who were pressed into service were not familiar with SHEF. Although parse/post software prints messages identifying SHEF errors, these messages must be manually processed if the data are to be used. Data were sometimes lost because forecasters were often too busy to process error corrections. There were also some types of errors that the software was unable to detect.

WSFOs had high praise for the Cooperative Observer Program throughout this event. Offices reported that they encountered very few problems with ROSA reports. Those few problems were the result of errors in coding. Early in the event, a considerable number of supplemental observations were received from the cooperative observers. As the flooding continued, however, these nonroutine observations decreased in number. This was due, at least in part, to the fact that some of the cooperative observers were personally impacted by the flood. The number of river gage observations also decreased as observers became increasingly threatened by the rising flood waters.

A widespread concern among NWS personnel in the affected area was the declining number of cooperative observers during the last decade. Virtually all of the offices in the area expressed a desire to increase the number of observers in their respective cooperative networks.

<u>FINDING 5.2:</u> There were a number of errors in SHEF-coded data.	<u>RECOMMENDATION 5.2:</u> The Office of Hydrology and regions should increase the emphasis on training in the use of SHEF for data exchange. Additionally, the NWS should increase the use of automated, quality-control procedures for data entry including those appropriate for ROSA.
<u>FINDING 5.3:</u> The number of stations in the NWS cooperative program has been declining. There is a need to recover lost stations.	<u>RECOMMENDATION 5.3:</u> Local NWS offices should explore ways to enhance their cooperative programs. The importance of the Cooperative Observer Program should be stressed to all current and prospective members of the cooperative network.
<u>FINDING 5.4:</u> Most offices would like to see the ROSA system expanded to include more cooperative stations.	<u>RECOMMENDATION 5.4:</u> Advantages of ROSA should be emphasized, and NWS should fund increased deployment of ROSA systems.

5.2.2 AUTOMATED SYSTEMS

A common data format is critical to effective, automated data exchange. SHEF is widely used by the hydrologic community at the Federal level. In addition, many state, regional, and local agencies also use SHEF.

One of the primary software systems supporting real-time data exchange in the NWS hydrology program is the Hydrometeorological Automated Data System (HADS). HADS, which is a software system running on the National Oceanic and Atmospheric Administration (NOAA) Central Computing Facility (NCCF) in Suitland, Maryland, puts data received from satellite communications links into a database and generates products for transmission over AFOS and over remote job entry (RJE) to RFCs.

5.2.2.1 DATA COLLECTION PLATFORMS

The greatest amount of automated hydrologic data is provided through data collection platforms (DCP): electronic devices connected to hydrometeorological sensors that observe and report through a geosynchronous satellite communications system at predetermined times (usually at 3-, 4-, or 6-hour intervals). Some DCPs are also capable of reporting at random times in response to changing conditions. Several Federal agencies in the flooded area, most notably the U.S. Army Corps of Engineers (COE) and the U.S. Geological Survey (USGS), own and maintain DCP systems. DCPs transmit a wide variety of data elements, including precipitation, river stage, reservoir pool elevation, and ambient air temperature. The DCPs observe data at frequent time intervals (as often as every 15 minutes) and store these data for subsequent transmission through the geostationary satellites to a ground station in Wallops Island, Virginia. From there, the data are immediately transmitted to the NWS Telecommunications Gateway and on to the NCCF where they are ingested into HADS. These data are made available to RFCs through their RJE system and over AFOS. WSFOs have access to the data through AFOS.

While NWS offices across the affected area had a variety of opinions regarding the accuracy of the DCP data, most of the offices expressed concern that the data were not received in a timely manner. Often the data were a few hours old when they were received. These delays were caused by a variety of factors including delays in assigned transmission windows for DCP data, inadequate DCP programming capabilities (i.e., no random channel), obsolete communications architectures, inadequate data management and quality-control software, and incomplete or improper use of HADS capabilities. The DCP river stage data were generally considered reasonably accurate. More frequent cases were noted, however, when rainfall data were found to be unreliable. As a result, some offices were reluctant to accept these data without additional checking and thus reduced the amount of rainfall input to the hydrologic models during this flood event.

<u>FINDING 5.5:</u> RFCs and WSFOs found the DCP river stage data to be generally useful, but cases were noted when significant formatting, decoding, and other errors occurred. One RFC felt that rainfall information from tipping bucket gages was so unreliable as to be unusable with current quality-control procedures. Consequently, the DCP precipitation data in the RFC's area were not used in the river and flood forecasts.	<u>RECOMMENDATION 5.5:</u> DCP data should be carefully scrutinized daily. When errors are detected, the agency owning that particular DCP should be contacted immediately. If the problem is not corrected within a reasonable time, proactive, follow-up contacts should be made when time permits. RFCs should improve their capabilities to display, verify, and quality control DCP rain gage data automatically to make maximum use of this valuable data source.
<u>FINDING 5.6:</u> Once transmitted, DCP data take too long to reach the RFC and WSFO databases.	<u>RECOMMENDATION 5.6:</u> NWS must ensure that the increased computing capabilities planned as a part of NWS modernization include adequate telecommunications and a robust data management system to alleviate these problems. The NWS should implement Automated Critical Reports in HADS as soon as possible to help alleviate this problem.
<u>FINDING 5.7:</u> In one instance, the RFCs had difficulty receiving data from HADS. The problem stemmed largely from the imprecise specification of the Time Periodic Report capabilities and occurred when retrieving COE DCP data from the Rock Island District.	<u>RECOMMENDATION 5.7:</u> The NWS should provide an in-depth training program to HADS focal points at RFCs and WSFOs. The NWS should implement Automated Critical Reports in HADS to facilitate data transfer.

5.2.2.2 LIMITED AUTOMATIC REMOTE COLLECTORS

Limited Automatic Remote Collectors (LARC), most of which are owned and maintained by the NWS, are connected to certain river and rain gages. They transmit river stage and precipitation data through a computer modem and voice telephone lines when interrogated. The Centralized Automated Data Acquisition System (CADAS) polls LARCs and supplies these data to NWS offices through HADS every 6 hours. LARCs can also be interrogated directly by telephone dial-up from individual offices.

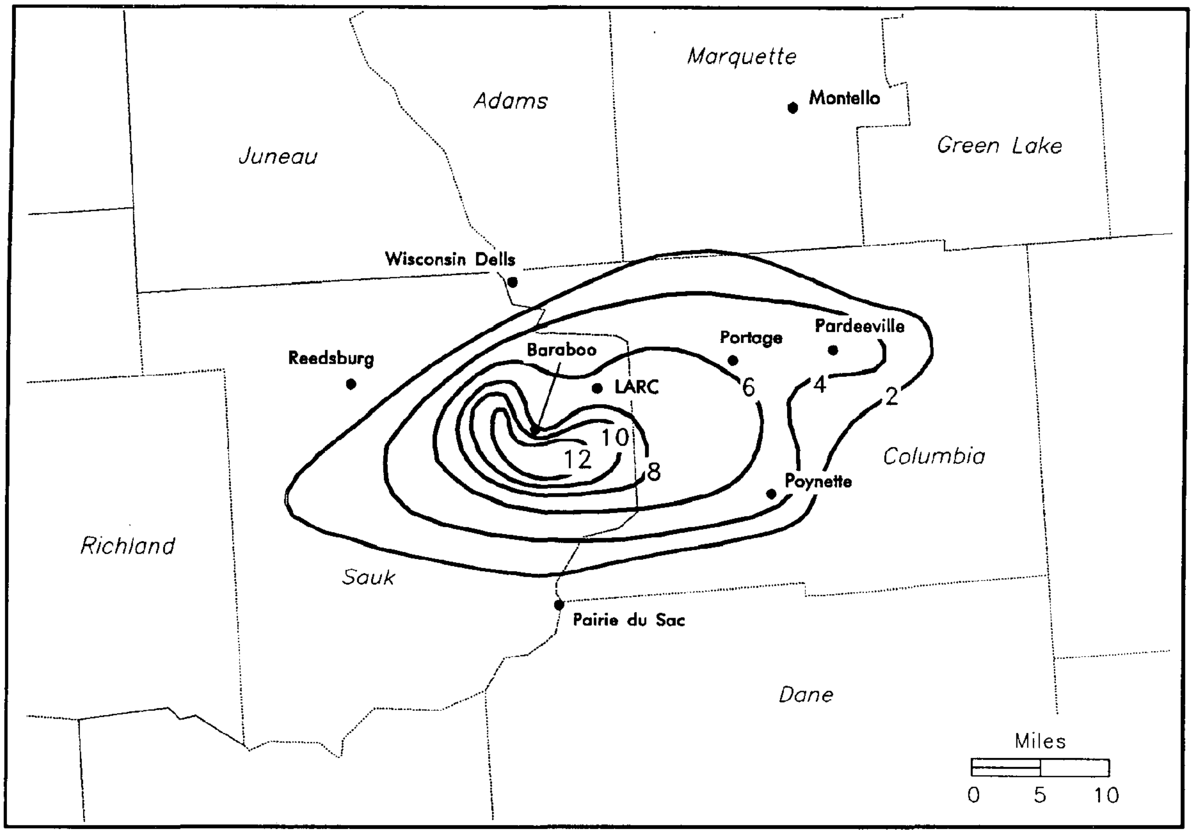


Figure 5-2. *Analysis of excessive rainfall (in inches) event near Baraboo, Wisconsin, for the 24 hours ending at 7 a.m. CDT on July 18, 1993. Most rain fell in 4 hours or less. Also shown is the location of the LARC.*

For the most part, LARCs performed well and were reliable throughout this event. There were several problems, however, which developed as flood waters escalated. Some offices reported that an upper stage limit of 32.7 feet had been programmed into certain LARCs. Consequently, when the river stage exceeded this limit, the LARC did not provide accurate river stage readings. Although NWS offices in North Dakota made a software modification in 1989 to remedy this problem, not all other offices were aware of the problem prior to this event. Other LARC-related problems included cases where manometers (used to measure river stages) connected to the LARCs flooded and where telephone lines were destroyed by flood waters.

LARCs were a valuable asset, not only to river forecasters but also to meteorologists involved with flash flood operations. One noteworthy example occurred on July 18, 1993. A LARC gage alerted forecasters at WSFO Milwaukee/Sullivan to heavy rainfall along the Baraboo River in the vicinity of a major public camping facility. This enabled the forecaster to issue a Flash Flood Warning with enough lead-time to allow people to evacuate. Massive flash flooding inundated the campground after 12 inches of rain had fallen 4 hours later. Figure 5-2 illustrates the rainfall distribution and the location of the LARC which prompted this timely warning. Without the LARC gage, the forecaster would have been unaware of the heavy rainfall. Many NWS offices expressed a desire to increase LARC coverage in their areas. There may not be sufficient CADAS capacity, however, to handle a large increase in the number of LARCs.

FINDING 5.8: Some NWS LARCs were unable to report data when the river stage exceeded 32.7 feet. The data register in a LARC can accept and report information from a total of 32,767 increments. If the decimal point is set to read out to one thousandth of a foot, the unit has a range of only 0.000-32.767.	**RECOMMENDATION 5.8:** Electronics Technicians should program LARCs so that they can accept and report data only to the nearest one hundredth of a foot (resulting in a total range of 00.00-327.67 feet). Electronics Technicians should also set up all appropriate LARCs so that the data range is broad enough to cover well beyond the greatest flood of record, as well as below the lowest low flow on record. The NWS Training Center should provide the necessary training to program and set up LARCs.
FINDING 5.9: Information obtained from LARCs demonstrably increased the ability of forecasters to issue accurate and timely forecasts and warnings.	**RECOMMENDATION 5.9:** High priority should be placed on the installation and maintenance of additional LARCs with attached, automated rain gages. The NWS should place a high priority on the Equipment Replacement Program needed to restore, to maintain, and, in some strategic locations, to add LARCs required to support the NWS hydrology program.
FINDING 5.10: Currently there are two CADAS computers. System A collects data from LARCs located in the Eastern and Central Regions, and System B collects data from LARCs located in the Southern and Western Regions. Each system is currently designed to collect data from 510 LARCs. System A presently collects data from 503 LARCs, and System B presently collects data from 350 LARCs. A better balance between the two systems may be possible to ensure that System A has room for more than the seven free spaces that now exist.	**RECOMMENDATION 5.10:** CADAS should be modified to collect data from more LARCs. Additionally, the CADAS interrogation programs should be updated to include newer telemetry systems such as Sutron 8200 data loggers with modems and Campbell CR-10 recorders. The NWS regions and the Office of Hydrology should establish an advisory board to recommend to the CADAS Program Manager appropriate modifications to the CADAS required to support the NWS hydrology program.

5.2.2.3 TELEMARKs/TALKAMARKs

Telemarks and Talkamarks are old telemetry equipment connected to some river gages and allow the gage data to be accessed over telephone lines. Inconsistencies and unexplained fluctuations in gage readings, and in some cases outright failures, were noted with Telemark/Talkamark equipment at some locations. Some of these variations appear to result from gage-mounting strategies and related hydraulic effects that had a considerable impact on Telemark and Talkamark readings. This effect seemed to be exacerbated as the magnitude of the flood increased.

The St. Charles County Emergency Management Agency (EMA) reported that the St. Charles Telemark gage regularly registered 0.2-0.8 foot lower than the adjacent staff gage during normal flow. During the flood event, the EMA reported that the Telemark gage read up to 2.5 feet below the staff gage. The degree of the drawdown effect[1] was loosely related to the river's rate of flow, but the relation could not be established using a simple correction factor. Consequently, the EMA increased the NWS stage forecast by the difference between the Telemark reading and the staff gage reading. This undoubtedly caused confusion among the residents of St. Charles County.

The St. Charles Telemark river gage apparently flooded out at near-record stage on or about August 1. Complete gage failures and inaccuracies in operational gages due to drawdown and other environmental problems made the official crest stage at St. Charles uncertain. The crest stage is important for future flood planning, levee construction, levee maintenance, and historical flood data.

Data from sites with multiple gages were often conflicting. Inconsistent data and hardware differences resulted in readings taken from more than one gage. There was confusion as to what value represented the "real" stage.

FINDING 5.11: Stream gage observations from multiple gages at single locations sometimes created confusion.	**RECOMMENDATION 5.11:** NWS policy should clearly designate the primary and secondary gages at those sites where multiple gages exist.
FINDING 5.12: In many cases, stream gages are mounted on the downstream side of piers and bridge pilings. At high flows, drawdown effects may lead to errors and inconsistencies in stage observations.	**RECOMMENDATION 5.12:** In a cooperative effort with the other agencies involved, the NWS should study the drawdown effect to better quantify this problem.

[1] The drawdown effect results from the positioning of the stream gage on the downstream side of a bridge pier or support to protect it from debris flow in the river. As the river rises and the current increases, an increase in velocity behind the obstruction tends to lower the stream level.

5.2.2.4 BACKUP OBSERVERS FOR AUTOMATED GAGES

For the most part, NWS offices had human observers available to back up automated equipment. Typically, these backup observations were reported to the WSFO/WSO by telephone. Some gages, however, are located at sites that became difficult or unsafe to access. Many observers were themselves flood victims and forced to evacuate the area. The only access to some gages was by boat, but this became hazardous as flows increased.

FINDING 5.13: There were numerous automated stream gage outages throughout the flood, as well as other cases with biased observations, that caused forecasting difficulties. Although backup procedures were often in place, they were not always adequate to meet the needs for a flood of this magnitude.	RECOMMENDATION 5.13: NWS offices should ensure that the backup plans for stream gages in their areas are as complete and thorough as possible. Guidelines should be established and tested to provide a smooth transition to the backup gage when a site's primary gage fails.

5.2.3 RADAR DATA

From 1990 to 1992, as part of the modernization and associated restructuring (MAR) demonstration, the NWS installed Weather Surveillance Radar 1988 Doppler (WSR-88D) radars at eight locations in the affected area: Goodland, Dodge City, Wichita, and Topeka, Kansas; Kansas City and St. Louis, Missouri; Chicago, Illinois; and Hastings, Nebraska (Figure 5-3). In addition to demonstrating its effectiveness in severe weather detection, the WSR-88D also proved helpful in forecasting flash floods and floods along rivers with rapid response times.

The primary hydrologic products currently available from the WSR-88D are the accumulated precipitation displays. These products use empirical relations to estimate rainfall amounts based on low-level precipitation echo intensity. The estimated precipitation amounts are summed over time periods of 1 hour, 3 hours, and for the entire time in which low-level precipitation echoes are detected (i.e., storm total). Figure 5-4 depicts a typical WSR-88D accumulated precipitation product.

Forecasters were generally pleased with the precipitation products generated by the WSR-88D. While the rainfall estimates were not perfect, they provided a good representation of the rainfall patterns when compared to rain gage measurements. In several cases, forecasters used these products to compose flash flood or flood warnings and provided longer lead-times than would otherwise have been possible. Since the precipitation products give estimates of rainfall in locations without rain gages, some of the flood events for which warnings were issued could possibly have gone unwarned without the WSR-88D data.

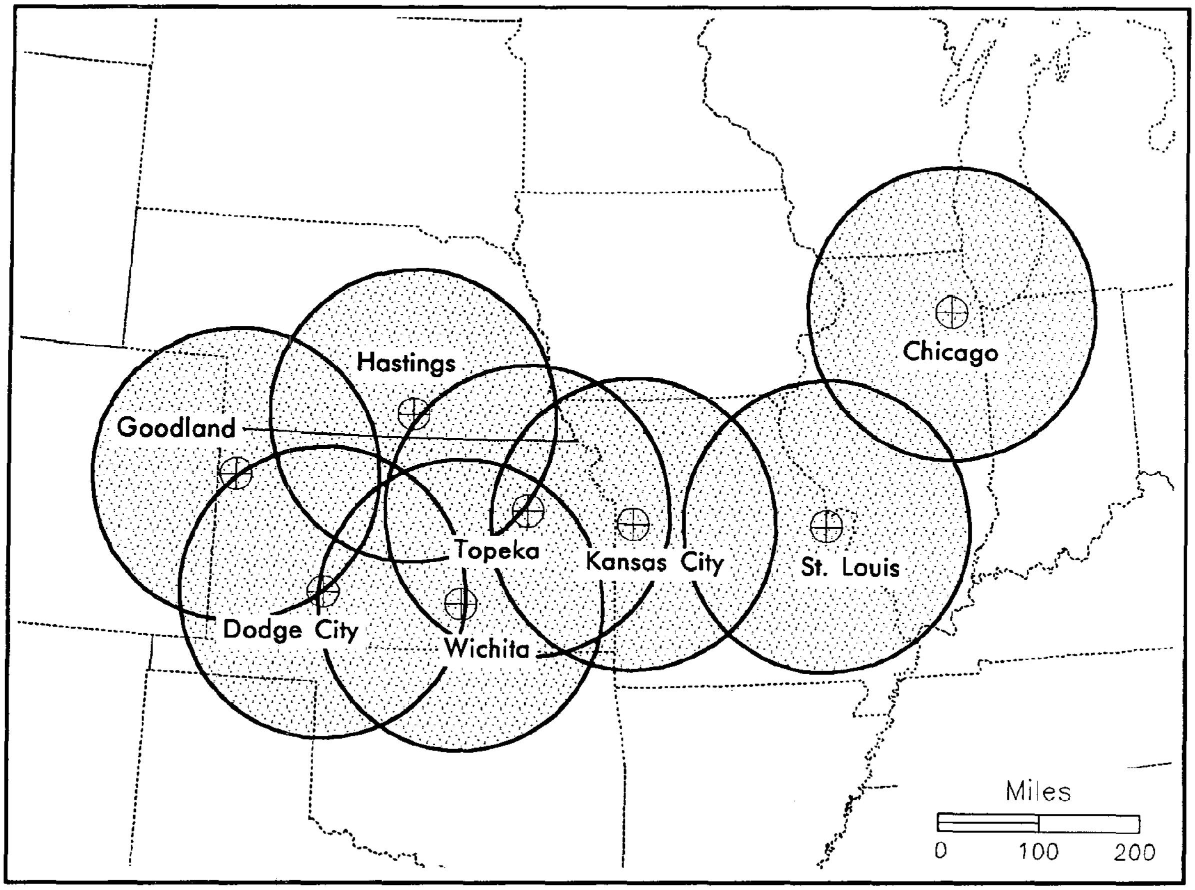


Figure 5-3. *Locations of WSR-88D radars in service in area affected by The Great Flood of 1993.*

Figure 5-4 illustrates the value of the accumulated precipitation product. The event occurred in northwestern Missouri during the night of August 11-12. The 1- and 3-hour precipitation estimates from the Kansas City WSR-88D suggested that flash flooding was eminent over Clay and Ray Counties, northeast of Kansas City. Flash Flood Warnings were issued well before the onset of flooding. Although property was damaged in the counties, no fatalities resulted. The maximum radar-estimated rainfall totals of 8-9 inches compared favorably with rain gage readings taken on the morning of August 12.

Although forecasters found the WSR-88D precipitation data useful, some areas for improvement were noted. Lightning strikes caused extended system outages at four radar sites. Forecasters at WSO Kansas City stated that during flooding or severe weather episodes, two people were needed to operate the WSR-88D Principal User Processor (PUP) efficiently. Additionally, the

WSR-88D does not have the same map backgrounds delineating drainage basins used for NWS forecasts. At the Missouri Basin RFC (MBRFC), because of sparse observer reports in the evening, WSR-88D precipitation data were used to estimate mean areal precipitation (MAP) for input to the NWS River Forecast System (NWSRFS) model. This was a difficult and imprecise process because the basin boundaries are not identical to those used by the RFC. Additionally, hard copies of precipitation estimates from the PUP are not the same scale as MBRFC base maps.

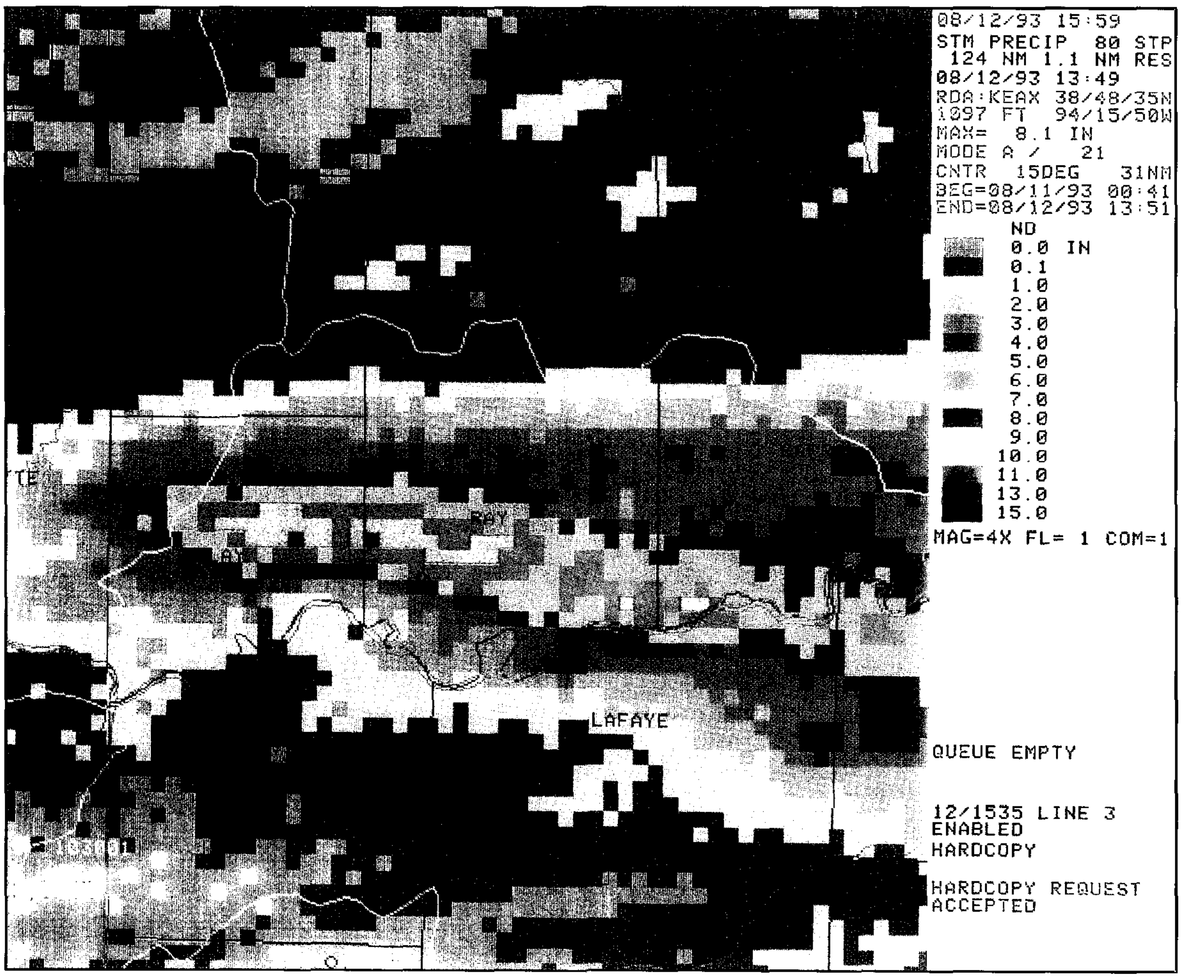


Figure 5-4. *Kansas City, Missouri, WSR-88D image showing storm total precipitation in northwestern Missouri ending at 8:51 a.m. CDT (13:51 UTC) on August 12, 1993.*

<u>FINDING 5.14:</u> Some WSR-88Ds in the flooded area (Chicago, Illinois; Hastings, Nebraska; St. Louis, Missouri; and Topeka, Kansas) experienced extended downtime as a result of lightning strikes and other system failures. The operational availability of the WSR-88Ds must be increased to the 96 percent level specified in the NEXRAD Technical Requirements to provide the continual time series of rainfall estimates needed for input to flood and flash flood models. Improved methods for lightning protection are being tested using the WSR-88D at Norman, Oklahoma.	<u>RECOMMENDATION 5.14:</u> Lightning protection and other system improvements for the WSR-88Ds required to achieve the contract-specified 96 percent operational availability must be given high priority.
<u>FINDING 5.15:</u> The WSR-88D PUP does not support digital output or provide sufficient capabilities to make effective, quantitative use of the WSR-88D precipitation estimates. Without the planned AWIPS interactive processing facility and the additional precipitation processing stages planned for AWIPS-era operations, the usefulness of WSR-88D precipitation data for quantitative hydrologic forecast applications is quite limited.	<u>RECOMMENDATION 5.15:</u> The NWS should aggressively pursue installation of AWIPS and AWIPS-type facilities for WSR-88D-equipped offices and for RFCs with significant coverage of their areas of responsibility by WSR-88D systems.
<u>FINDING 5.16:</u> To use the WSR-88D precipitation products as input into the river forecast models, RFC staff had to manually estimate MAP values using hard-copy printouts. This method is imprecise and time-consuming.	<u>RECOMMENDATION 5.16:</u> Improved computer technology at the RFCs, which is a part of NWS modernization, will help remedy this problem. Every opportunity should be taken to accelerate the implementation of computer processing capabilities at the RFCs. Also, map backgrounds outlining MAP areas should be added to the WSR-88D database.

5.2.4 OTHER DATA SOURCES

The systems listed above served as the primary means of data acquisition. Additionally, other systems also provided valuable information. The following subsections describe these additional data sources.

5.2.4.1 SATELLITE INFORMATION

Both geostationary and polar-orbiting satellites continue to provide worthwhile information that is used at a number of points in the forecast system. Geostationary satellites provide a continual view of the atmosphere from the global scale down to flash-flood scale. Hemispheric images are useful in preparing synoptic analyses, for example, by identifying such features as water vapor plumes that are not commonly detected by other observing systems. Satellite information is routinely used in the preparation of quantitative precipitation forecasts (QPF) (see Section 5.2.4.2).

Mesoscale convective systems are monitored by the Synoptic Analysis Branch (SAB) of the National Environmental Satellite, Data and Information Service (NESDIS). Graphic estimates of rainfall are generated on the Interactive Flash Flood Analyzer (IFFA) in the SAB. During periods of heavy precipitation, the SAB provides quantitative rainfall estimates that are transmitted over AFOS to support operational forecasting in field offices. Currently, IFFA-derived graphical products showing isohyetal precipitation estimates are not available over AFOS. While not all WSFOs relied to the same degree on these estimates, some offices found them quite useful. Neither the NCRFC nor the MBRFC routinely use satellite precipitation estimates in their operational models.

Soil moisture monitoring techniques based on data from polar-orbiting satellites are being developed. This information received wide publicity during a briefing by Vice President Gore in mid-July. It is possible that satellite-derived soil moisture estimates could help to specify soil moisture states in the hydrologic modeling system. Details of satellite-derived precipitation and soil moisture estimates are given in Appendix C.

<u>FINDING 5.17:</u> Graphical representation of satellite-derived isohyetal patterns are not available over AFOS.	<u>RECOMMENDATION 5.17:</u> The NWS and NESDIS should make IFFA-derived precipitation estimates routinely available over AFOS during flash flood events.

FINDING 5.18: The operational use of satellite precipitation estimates has not yet reached its full potential.	RECOMMENDATION 5.18: The NWS and NESDIS should develop a procedure to integrate IFFA-derived rainfall estimates with radar and rain gage observations. The procedure should be flexible enough to compensate for missing observations.
FINDING 5.19: Satellite soil moisture estimates are not currently used in operational river forecasting.	RECOMMENDATION 5.19: NOAA should implement techniques to use remotely sensed (i.e., airborne and satellite) and in situ soil moisture observations in river and flood forecasting.

5.2.4.2 QUANTITATIVE PRECIPITATION FORECASTS

While RFCs did not objectively and routinely use QPFs as direct input to river forecast models during this flood, the NCRFC did subjectively use QPF information. QPF values were broken down subjectively as an MAP value by RFC staff and incorporated in the hydrologic modeling process. This approach was used extensively over Iowa where the state maps were used by WSFO forecasters to plot QPF. Additionally, WSFO and RFC forecasters used QPFs as guidance to large-scale precipitation patterns. The development of QPF products and their potential skill and use in hydrologic forecasting are discussed in detail in Appendix B.

5.2.4.3 ALERT SYSTEMS

A Local Flood Warning System (LFWS) is a community or locally based system consisting of rainfall, river, and other hydrologic gages; hydrologic models; a communications system; a community flood coordinator capable of issuing a flood warning; and, in some cases, volunteer personnel. The purpose of the system is to provide emergency service officials with advanced flood information that can be readily translated into response actions. The Automated Local Evaluation in Real-Time (ALERT) system is a typical automated LFWS that was developed by the NWS California-Nevada RFC. Several municipalities in the flooded area were equipped with ALERT systems. ALERT systems are designed to meet the needs imposed by small, fast-response river systems. The basic components of the ALERT LFWS consist of:

1. Automated event and/or periodic reporting precipitation and river gages,
2. Automated data collection and processing equipment (base station),
3. Computerized hydrologic and meteorologic analysis techniques, and
4. Dissemination of warnings and forecasts.

ALERT systems may also contain a hydrologic model, as well as some form of hydrometeorological data analysis techniques and procedures. These systems proved their value in several cities. In at least one case, however, it was not technically possible to transfer NWS products to the ALERT base station.

FINDING 5.20: In at least one case, the hardware configuration of the ALERT system made it technically impossible to transfer NWS river forecasts and warnings to the ALERT system.	**RECOMMENDATION 5.20:** NOAA Weather Wire is the primary method of NWS product distribution. Nonetheless, NWS forecast offices should ensure that appropriate memoranda of agreement are in place with local parties for appropriate two-way exchange between ALERT systems and the NWS. Where technically feasible, ALERT systems should be modified to facilitate exchange of hydrometeorological data, forecasts, and warnings between ALERT systems and NWS offices. Additionally, local hydrometeorological detection systems, such as ALERT, should be tested periodically to ensure that they are functioning properly.

5.2.4.4 SKYWARN SPOTTERS

Across the affected area, thousands of amateur radio operators, law enforcement and fire officials, and members of the public serve as volunteer weather spotters in the NWS SKYWARN program[2]. Spotters played an important role in reporting significant weather events, especially in North and South Dakota, where the spotters seemed well-versed in flood reporting procedures. In other areas, however, the SKYWARN program was less effective in providing flood-related information.

---

2 In general, SKYWARN spotters are a group separate from cooperative observers. The primary responsibility of SKYWARN spotters is to monitor their areas for signs of severe weather (e.g., tornadoes, lightning, high winds, flash flooding) and to report to a local NWS office when such conditions are observed. Reporting is done only as a result of a given event and typically does not include quantitative weather observations. Many SKYWARN observers report over HAM radios. Cooperative observers, however, usually report quantitative information (e.g., river stages, precipitation, temperature, etc.) on a regular basis while sometimes providing supplemental reports of unusual conditions. Many cooperative observers report over telephone lines. The remainder mail in their observations, which are not used for operational forecasting but for climatological purposes.

<u>FINDING 5.21:</u> There was variation in the effectiveness of reporting flood conditions by SKYWARN observers.	<u>RECOMMENDATION 5.21:</u> NWS Headquarters should include in the SKYWARN spotter training syllabus material on flood reporting. Local offices should educate observers about effective flood-reporting procedures. Spotters should be encouraged to submit reports when heavy rain and/or flooding occurs (which may require making affordable rain gages available).

5.2.4.5 STREAMFLOW MEASUREMENTS

Other government agencies are sources of valuable streamflow and precipitation data. Excellent coordination is imperative to ensure that these data are received in a timely manner to allow for thorough analyses. The COE contracted with the USGS to collect several hundred special discharge measurements to better quantify volumes of flow and stage-discharge relations at key locations. Most of these extremely valuable special measurements were made available to RFCs and some WSFOs. The efficiency and timeliness of the data transfer, however, was slowed by the lack of adequate communications links. Nevertheless, the special discharge measurements were used by the RFCs whenever available to assess existing river conditions for input to their river forecast procedures.

<u>FINDING 5.22:</u> Existing stage-discharge relations were exceeded at approximately 100 sites. During the most severe flooding, flow measurements were too sparse.	<u>RECOMMENDATION 5.22:</u> Through collaborative efforts with principal NOAA cooperators, resources (including those to update streamflow measurements and/or perform analyses) need to be made avail-able so that new stage-discharge relations can be developed for these sites.

Finding	Recommendation
<u>FINDING 5.23:</u> There were periodic coordination and communications problems associated with data exchange between Federal agencies. For example, appropriate NWS offices did not always receive, in a timely manner, the special streamflow measurements made by the COE or USGS. Additionally, appropriate NWS offices were not always made aware of the streamflow measurement schedules; consequently, it was impossible to infer when NWS offices did not have specific stream discharge measurements. Computer hardware limitations sometimes made it difficult to distribute NWS products to end-users. Consequently, NWS offices were, on occasion, required to fax forecasts and products to end-users.	<u>RECOMMENDATION 5.23:</u> The COE, USGS, and NWS should improve communications links among themselves and with other Federal, state, and local agencies. Specifically, the three agencies should ensure that the data collection schedules and the data distribution mechanisms for stream discharge measurements and other valuable hydrometeorological data sets are well understood and documented. In some cases, computer-to-computer links must be developed and/or upgraded (see Recommendation 6.19).

5.2.4.6 STRANGER REPORTS

"Stranger reports" include information not normally used in the forecast process. Frequently they are precipitation and river stage observations received from unofficial sources. In addition to providing valuable information to such products as Special Weather Statements and Flash Flood Statements, they can be a source of supplemental information that can improve RFC forecasts. Precipitation data from stranger reports cannot, however, conveniently be input into NWSRFS in its present form. RFC personnel must input these reports at defined, nearby missing stations, or manually estimate affected MAP areas. Because of this labor-intensive process, stranger reports provided by WSFOs/WSOs are not usually used.

Finding	Recommendation
<u>FINDING 5.24:</u> Precipitation from stranger reports cannot conveniently be input into NWSRFS in its present form. RFC personnel must input these reports at defined nearby missing stations, or manually estimate affected MAP areas. Because of this labor-intensive process, stranger reports provided by WSFOs/WSOs are not usually used.	<u>RECOMMENDATION 5.24:</u> The OH should make the necessary effort to modify the MAP preprocessor so it can accommodate stranger reports.

5.2.4.7 AIRBORNE SNOW AND SOIL MOISTURE SURVEY

The Office of Hydrology and the National Operational Hydrologic Remote Sensing Center maintain an Airborne Snow Survey Program. Low-flying aircraft are used to make airborne measurements of natural terrestrial gamma radiation along selected flight lines. The gamma radiation data are used to infer snow water equivalent with an error of less than 1 cm. Additionally, the airborne technique is also used to infer soil moisture to a depth of 20 cm under snow-free conditions. The Airborne Snow Survey Program maintains a flight line network covering large portions of 26 states and 7 Canadian provinces. The airborne snow water equivalent data collected in the winter, and the soil moisture data collected in the late fall, are used by NWS hydrologists in RFCs and WSFOs when assessing the potential for significant spring snowmelt flooding and when making water supply forecasts in the West.

Airborne snow surveys were conducted over the Upper Midwest during the winter of 1993. Based partly on the airborne snow water equivalent data collected over the Upper Midwest in February and March 1993, the NCRFC issued a spring flood outlook on March 25 that called for moderate to major flooding across large regions of Iowa. In a few limited cases, however, inadequate late-winter and early-spring, ground-based, snowpack observations in remote areas of the Upper Midwest led to false assumptions that much of the snow water equivalent had run off or had been absorbed into the ground. In reality, much ice and snow water equivalent remained. Runoff into some rivers was much higher than expected and resulted in significant flooding. Spring snowmelt in the Upper Midwest primed the region for the major flooding which was to follow. Airborne gamma radiation snow surveys provided essential information in evaluating water content of the snowpack and subsequent runoff.

Airborne snow surveys depend on an accurate knowledge of soil moisture to determine the amount of water contained in the snowpack. The Great Flood of 1993 left above-normal soil moisture conditions. To ensure accurate airborne snow water equivalent measurements in the spring of 1994, airborne soil moisture measurements should be made in the fall of 1993. Soil moisture information is also critical in operational river forecasting. The soil moisture information collected in support of airborne snow estimation will provide information used in routine forecast operations both this fall and in the spring.

FINDING 5.25: Much of the early flooding (March, April, and May) in the Upper Midwest was aggravated by above-normal snow cover conditions that developed during the winter and spring of 1993. WSFO Sioux Falls indicated that additional snow water equivalent data would have been valuable before the onset of the 1993 spring snowmelt flooding. The NWS maintains a dense network of airborne flight lines in the Upper Midwest. The airborne snow survey program provides reliable, real-time airborne snow water equivalent measurements over the flight line network for use by NWS field offices when assessing the potential for spring snowmelt flooding.	**RECOMMENDATION 5.25:** Hydrologists in the regional, RFC, and WSFO offices should request airborne snow surveys over specific areas within their respective regions of responsibility when snow water equivalent is expected to be a major factor associated with spring flooding in the Upper Midwest.
FINDING 5.26: The Great Flood of 1993 left large regions of the Upper Midwest with much above-average soil moisture conditions in the fall of 1993. The existing network of airborne flight lines can be used to make airborne soil moisture measurements in the late fall of 1993. Fall airborne soil moisture measurements are used by NWS hydrologists at the NCRFC when assessing the potential for future flooding during each winter and spring.	**RECOMMENDATION 5.26:** The Office of Hydrology should make a comprehensive airborne soil moisture survey over the existing flight line network in the Upper Midwest to provide an assessment of soil moisture conditions in the late fall of 1993.

5.3 TELECOMMUNICATIONS

While much of the telecommunications activity associated with the flood involved the dissemination of information to emergency managers and other users, telephone systems were used for the acquisition and relaying of some data as well. Cooperative observers and LARCs were accessed by telephone (see Sections 5.2.1 and 5.2.2.2); and, in some cases, EMAs relayed flood and evacuation information to NWS offices by phone. Telephone service was generally satisfactory during the event, but there were some flooded areas in which the telephone lines were destroyed. As a result, contact was lost with some key agencies and data sources.

There is no existing, high-speed, wide-area communications network between NWS offices and other key governmental water agencies. RFCs have a "Gateway System" which provides two-way communication between the RFCs and selected Federal cooperators. The current system runs on a mid-1970s minicomputer. The system is so old, for example, that the maximum asynchronous baud rate attainable is 4800.

As discussed in Chapter 4, operational forecasting is typically done on computer systems located at the NCCF in Suitland, Maryland. The RFCs are connected to the NCCF via RJE by low-speed, 9600-baud communications circuits. During extreme flooding, such as experienced in The Great Flood of 1993, the number of required forecasts and updates becomes enormous. Current communications links supporting RJE were often not fast enough to meet the elevated operational needs of the RFCs. Major improvements in both the level of independence from the NCCF and the communications capacity for the RFCs in the modernized NWS should alleviate most communications problems with the NCCF.

Over the weekend of July 9-11, significant communications problems occurred in Suitland as a result of a power outage caused by an automobile accident that knocked down a utility pole. The resulting power outage affected communications equipment housed in a building separate from the NCCF itself and effectively severed RFC RJE communications. Auxiliary power had to be used during this event. There were significant periods, however, when there was no 9600-baud dedicated link between any of the RFCs and the NCCF during the time when backup power was being brought on-line. During those periods, the RFCs were required to use slower (4800-baud) backup lines to connect with the NCCF. The two RFCs in the area affected by The Great Flood of 1993 (MBRFC and NCRFC) were given highest priority for the available backup lines and experienced a complete outage of NCCF telecommunications for only a 4.5 hour period; other RFCs were without NCCF telecommunications for as much as 22 hours. Although this event did not have a serious service impact, it clearly illustrated the dependence of the RFCs on the NCCF and the vulnerability of the NWS Hydrologic Service Program should a disastrous failure occur.

AFOS is the operational communications system currently used by the NWS and is based on early 1970s minicomputer technology. The AFOS system at the RFCs is used as a communications system for disseminating forecast products to WSFOs. While there are concerns about its inability to move information rapidly, in spite of its age, it proved remarkably reliable. The System-Z AFOS upgrade increased system stability.

The telecommunications path for certain Canadian information routes data from the National Center in Toronto, through NMC, to NWS WSFOs. These data are often delayed or unavailable by this pathway, but WSFO Bismarck dials directly into Environment Canada, thus bypassing the national route.

FINDING 5.27: Telephone lines to certain key stream gages were destroyed by the flood.	**RECOMMENDATION 5.27:** The use of alternative data acquisition systems for stream gage data (e.g., radio, satellite, or meteorburst transmission technology) should be explored to build redundancy into the system at key locations.
FINDING 5.28: The current telecommunications environment for interagency data exchange relies on limited, voice-grade, two-way links. This telecommunications approach did not provide an adequate level of service to the COE and other Federal, state, and private cooperators during The Great Flood of 1993. Moreover, it is completely inadequate to support even higher rates of data exchange. Higher levels of service can be achieved now with available telecommunications technology.	**RECOMMENDATION 5.28:** The NWS should implement plans for modern telecommunications and information exchange with major water management cooperators and conduct a demonstration of these capabilities as soon as possible.
FINDING 5.29: WSFO Bismarck dials directly into the Environment Canada system for data. There are frequent problems, however, in routing data from the National Center in Toronto through the National Meteorological Center to the WSFO. These data are often delayed or unavailable.	**RECOMMENDATION 5.29:** NWS and Environment Canada field offices should continue their good working relations. The National Meteorological Center and Environment Canada's National Center should investigate the possibility of improving the interface between their computer systems.
FINDING 5.30: There is no backup should there be a disastrous failure of the NCCF for those RFCs that are still dependent on the facility.	**RECOMMENDATION 5.30:** As quickly as possible, NOAA should develop disaster contingency plans to use distributed AWIPS-type RFC systems to provide backup for NCCF-dependent RFCs until AWIPS is deployed.

FINDING 5.31: Despite the limited capabilities of AFOS and the fact that those capabilities were pushed to their limits throughout the flood event, AFOS generally performed in a reliable and stable manner. Concern was expressed that AFOS, which has exceeded its original life expectancy, will not be able to continue reliable performance.	**RECOMMENDATION 5.31:** AFOS must be maintained as a highly reliable operational NWS system until replaced by AWIPS at the earliest possible date.
FINDING 5.32: Communications between RFCs and the NCCF are critical to RFC operations and are a weak link in the current river forecast system.	**RECOMMENDATION 5.32:** The NWS must evaluate its backup procedures to ensure there is sufficient communications capacity to support operations during major flooding.
FINDING 5.33: Current RFC communications capabilities are too slow for extreme loads generated at times of widespread major flooding. During The Great Flood of 1993, a workaround was developed to operate both the dedicated 9600-baud circuit simultaneously with the 4800-baud dial backup circuit for the North Central RFC. This was effective in increasing the communications capacity by 50 percent, but it is expensive and has no backup.	**RECOMMENDATION 5.33:** All RFCs should be made aware of the potential use of the dial backup RJE circuit as an emergency, temporary boost to their NCCF telecommunications capabilities.

5.4 FACILITIES

RFCs, WSFOs, and WSOs conduct their operations in a wide variety of facilities. The size of the staffs and the programs maintained by the various offices are the primary factors used to determine the space and resources available at a particular facility. While most NWS staff felt that their facilities were adequate for conducting their operations, concerns were voiced regarding a lack of flat workspace for oversize topographic maps and other bulky materials needed for the proper analysis of hydrometeorological conditions.

FINDING 5.34: Some offices lack large workspace areas for use of bulky items such as topographic maps.	RECOMMENDATION 5.34: The layout of new facilities being built as part of MAR should be configured to consider the requirement for flat workspace. Where practical, current offices should be rearranged to accommodate this requirement.

5.5 CURRENT HYDROLOGIC FORECAST SYSTEM CAPABILITIES AND LIMITATIONS AT THE RFC AND HYDROLOGIC SERVICE AREA OFFICES

The ability of an RFC to produce timely and accurate hydrologic forecasts hinges on the quality of the hardware, hydrologic software, and communications systems available. Similarly, the ability of a Hydrologic Service Area (HSA) office to disseminate locally, to update quickly, or to produce its own forecasts is closely tied to the availability of local, interactive processing capabilities. Neither RFC nor HSA offices in the affected area have the necessary software and hardware to systematically support on-site, local processing and interactive execution of the latest hydrologic software necessary to carry out their missions effectively.

5.5.1 CURRENT HYDROLOGIC HARDWARE/SOFTWARE SYSTEMS AT THE RFC

For the most part, both the MBRFC and NCRFC have old and outdated hardware, hydrologic software that executes primarily on remote mainframe computers, and communications circuits that are limited and slow. One RFC did not have an Electronics Technician on staff to keep systems operational. Often forecasters were required to perform Electronics Technician duties.

At both RFCs, hydrologic forecast systems are executed in a 1960s batch-oriented environment. RFCs submit forecast runs known as "jobs" to a mainframe computer located at the NCCF, via RJE. Hydrologic forecast model output is returned to the RFC in a text format that is either sent to a line printer or displayed (rotated by 90 degrees) on a CRT (monitor). The display of the forecast hydrograph lacks the detail necessary to discern many hydrologic features. If even one simple change is needed, the forecaster must create a "run-time modification," submit the modification to the mainframe computer via RJE, and wait. The entire process is slow and time-consuming.

The MBRFC has a PRIME minicomputer that is used to manage hydrologic data locally and to execute part of the RFC's hydrologic software. Although useful, the PRIME is currently 8-10 years old and has an extremely slow processor. For example, some data-processing tasks take up to 2 hours.

The NCRFC has implemented a local network of microcomputers that is used to help expedite forecast operations. This network served well during the flood but does not include the processor for executing hydrologic models. The NCRFC still relies on a batch-oriented RJE with remote processing on the mainframe computer for its forecast operations.

<u>FINDING 5.35:</u> The posting, data management, and quality control of hydrometeorological data, in general, is too slow, laborious, nonsystematic, and incomplete.	<u>RECOMMENDATION 5.35:</u> The AWIPS system (which will employ sophisticated graphics, database, and computing capabilities that far exceed those currently in use) should eliminate system reliability problems and facilitate data management tasks. It is essential that AWIPS be implemented as soon as possible.
<u>FINDING 5.36:</u> Users indicated a need for more frequent river forecast updates. The RFC model update cycle is dependent on batch computer operations over a communications link to the NCCF. This problem was less acute for the MBRFC because some forecast operations are run locally on a minicomputer. Batch-mode operations not only contribute to delays in forecast updates but also inhibit the forecaster from gaining the level of insight into hydrometeorological conditions that is possible with local, interactive processing. This contributed to delays in forecast release times.	<u>RECOMMENDATION 5.36:</u> The NWS should move as quickly as possible to install on-site, interactive forecast systems in RFCs to speed up production of forecast products, including updated river forecasts and contingency forecasts based on various precipitation scenarios. Although the AWIPS system will ultimately support this interactive RFC environment completely (see Recommendation 5.35), opportunities to take advantage of AWIPS-type facilities and/or early AWIPS platforms must be maximized. Additionally, HSA offices should work with the RFCs to coordinate event-driven updates that provide users with timely flood warning information.
<u>FINDING 5.37:</u> Various system hardware problems and the lack of technician support required hydrologists to perform electronic maintenance functions to keep systems operating.	<u>RECOMMENDATION 5.37:</u> Contingency plans should be developed by the Office of Systems Operations and the NWS regions to ensure that all RFCs have adequate electronic systems support during critical flood events.

5.5.2 CURRENT HYDROLOGIC HARDWARE AND SOFTWARE SYSTEMS AT THE HSA OFFICES

The main computer and communications system at offices with HSA responsibility is AFOS. This technology is old, outdated, and does not provide the appropriate computer architecture to develop or to execute data-intensive, interactive hydrologic forecast models. Moreover, AFOS does not contain a robust database management capability needed to run hydrologic models.

The Central Region has provided a microcomputer to each Service Hydrologist to support the Service Hydrologist Information Management System, known as SHIMS. This has greatly helped the HSA office to organize the administrative part of the Service Hydrologist Program. There is no current national or Central Region program, however, for providing microcomputers to HSA offices in support of automated data collection and/or automating simple hydrologic procedures. Most HSA offices indicated the need for additional computer capability to help support the NWS hydrology program.

5.6 MODERNIZED HYDROLOGIC FORECAST SYSTEM CAPABILITIES AT THE RFC AND HSA OFFICES

Many of the limitations and problems associated with the current hydrologic forecast systems at RFC and HSA offices will be resolved when the offices receive the modern technologies associated with MAR. Users requested more accurate, more site-specific, and more timely hydrologic forecast service. The implementation of advanced technology, such as the AWIPS, the WSR-88D, and the Automated Surface Observing Systems, known as ASOS, coupled with components of new hydrologic software, will allow Weather Forecast Offices (WFO) the ability to satisfy these needs.

5.6.1 MODERNIZED HYDROLOGIC FORECAST SYSTEM CAPABILITIES AT THE RFC

The hydrologic forecast system capabilities at an RFC in the modernized NWS will increase dramatically. The most significant change will be the use of an on-site, interactive forecast system in real-time coupled with high-resolution precipitation data. The interactive system will execute in a distributed network environment and will provide forecasters a graphical user interface for easy access and flexibility. Other features of the system will allow a choice of models and procedures, user control for selection of models and methods used, and procedures for easily adding new models to keep up with scientific and technological changes. Each RFC will be able to process large amounts of data and quickly produce forecasts for hundreds of locations.

The ability to process precipitation data automatically will constitute another dramatic change. The ability to derive and to use spatially and temporally detailed precipitation estimates in advanced hydrologic models will revolutionize the science of surface water hydrology. The precipitation processing system will ingest, merge, and mosaic precipitation estimates from multiple WSR-88D radars, observed precipitation data from rain gages, and satellite precipitation estimates. The result of this processing will be timely estimates of gridded precipitation fields used as input to the interactive forecast system.

The use of a modern database management system will be another significant change that will provide an efficient means to manage real-time and historic data, model parameters, forecasts, rating tables, and gage and station information.

5.6.2 MODERNIZED HYDROLOGIC FORECAST SYSTEM CAPABILITIES AT THE HSA OFFICES

In the modernized NWS, the WFO will have HSA responsibility. The hydrologic forecast system capabilities at the WFO will increase dramatically. WFOs will receive real-time advice and counsel along with improved support products from the RFCs and will use the vast hydrometeorological databases and capabilities produced by new technologies. WFOs will be able to issue timely, site-specific warnings and follow-up statements for floods and flash floods, as well as other hydrologic products.

WSFOs did not have the data and tools necessary to produce local forecasts or to update and customize RFC guidance. (See also Chapter 2 and Section 4.7.3.) One of the most important advancements at the WFO will be the capability to produce hydrologic forecasts and warnings at the local site. The HSA offices will have an interactive hydrologic forecast model running locally. Although RFCs will be responsible for maintaining the integrity of the local forecast model, the HSA office will be the principal user in real-time situations. Another significant improvement will be the availability of high-resolution precipitation data from the WSR-88D radars.

CHAPTER 6

WARNING AND FORECAST SERVICES

6.1 INTRODUCTION

The Great Flood of 1993 made unprecedented demands on the National Weather Service (NWS) for warning and forecast services. Thousands of forecasts were produced and issued under extremely complicated hydrometeorological conditions. There were long periods of widespread, heavy rains. Massive levee breaks occurred at random. In addition, complicated backwater situations made it difficult for personnel to "keep up" with timely information. In spite of the complexity and scope of the event and the outdated technologies in most NWS offices, NWS personnel provided outstanding service.

The magnitude of the event prohibits a full and detailed description of the services provided by the NWS. A summary of the forecast and warning services is represented by an overview of products issued from all offices. More detailed analyses of the forecast service are provided for several selected forecast points on the upper Mississippi and Missouri Rivers. Technical details of the forecast service are provided in two case studies.

6.2 RESPONSIBILITIES OF RIVER FORECAST CENTERS

The Missouri Basin River Forecast Center (MBRFC) and the North Central River Forecast Center (NCRFC) prepare river forecasts in their respective areas of responsibility (see Figure 6-1). Forecasts are prepared for site-specific locations called "river forecast points." A river forecast point represents a "reach" along a river above and below the gaged site. In most cases, it has an associated stream gage and a stage-discharge rating (see Section 4.3.1.2). The River Forecast Centers (RFC) also produce flash flood and other hydrologic guidance products for their areas. Guidance products are disseminated to Weather Service Forecast Offices (WSFO) and Weather Service Offices (WSO) that have Hydrologic Service Area (HSA) responsibility.

The NCRFC is responsible for preparing river forecasts for the Mississippi River drainage from its headwaters to Chester, Illinois, excluding the Missouri River basin. Its area of responsibility encompasses the Red River of the North to the Canadian border, including the Souris basin in North Dakota and the Roseau River in Minnesota; the Rainy River in Minnesota; the mouth of the Big Muddy in Illinois; and the Great Lakes tributaries in Michigan, Minnesota, Wisconsin, Illinois, and Indiana, except the Maumee basin. The "hand-off" point to the Lower Mississippi River Forecast Center (LMRFC) is at Chester, Illinois, on the Mississippi River. The NCRFC has 456 river forecast points in its area of responsibility. Of these, 298 points are located in the Mississippi drainage and 44 are in the Red River of the North.

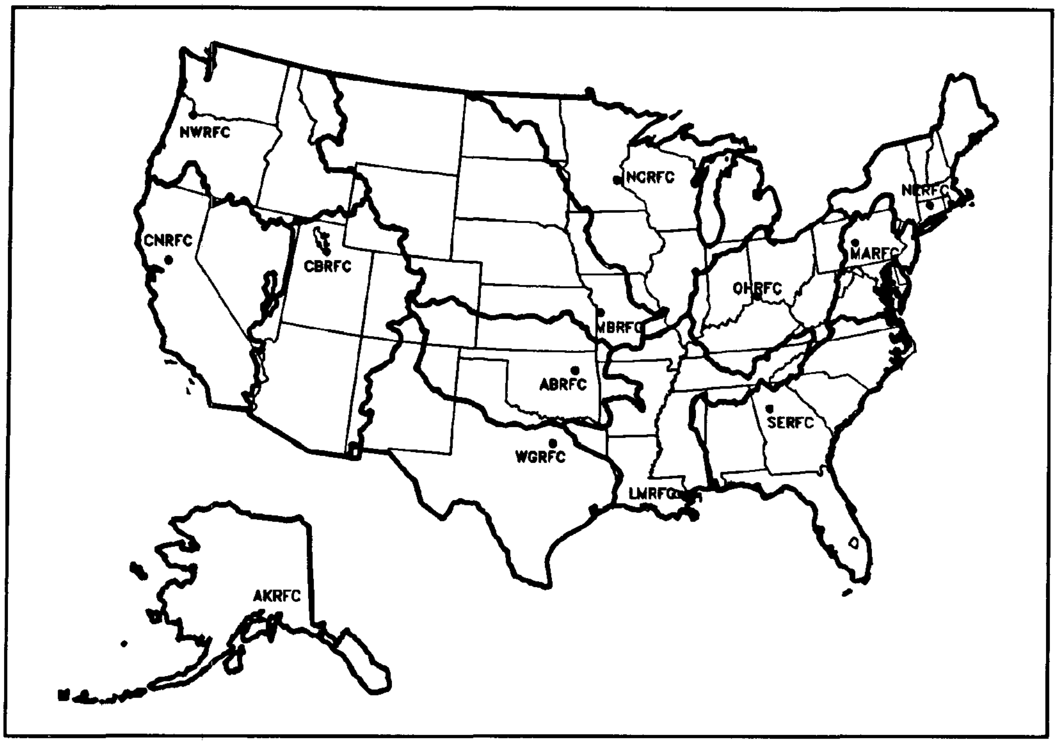


Figure 6-1. *Locations of, and areas served by, the 13 NWS River Forecast Centers.*

The MBRFC prepares river forecasts for the main stem and all tributaries of the Missouri River down to St. Charles, Missouri. The forecast point at Hermann, Missouri, is the hand-off point to the NCRFC. MBRFC is responsible for 446 river forecast points. A summary of the number of forecast points for each HSA office, by RFC, is shown in Table 6-1.

6.3 OFFICES WITH HYDROLOGIC SERVICE AREA RESPONSIBILITY

Selected NWS offices, usually WSFOs, are assigned HSA responsibility. The HSA office takes the numerical river forecasts, produced by the RFCs, adds local information (e.g., current river stage information, "call-to-action" statements, flood stage, levee elevations, and expected areas of inundation), and issues river forecasts, flood warnings, and other hydrologic products. These products are disseminated to the general public, specialized users, and the media through various means (see Chapter 7). The HSA office must also be alert to hydrometeorological situations that have a potential for flood-producing rains. Due to rapidly changing conditions, they actively collect data and issue preliminary forecasts and warnings when RFC guidance is not available. WSFOs (usually having HSA responsibility) also issue flash flood watches and other meteorological forecast products.

Table 6-1. *Number of river forecast points by RFC and HSA.*

NWS OFFICE WITH HSA RESPONSIBILITY	HSA ID	NCRFC FORECAST POINTS	MBRFC FORECAST POINTS	ADAPTIVE FORECAST POINTS*
Bismarck	BIS	60	13	0
Chicago	LOT	104	-	0
Des Moines	DMX	69	32	0
Minneapolis	MSP	57	-	1
Milwaukee	MKE	40	-	0
Omaha	OMA	-	98	6
St. Louis	LSX	30	64	0
Sioux Falls	FSD	-	42	0
Topeka	TOP	-	99	0

* Adaptive forecast points are points where hydrologic relationships are developed using information from nearby official river forecast points. Once developed, these relationships enable NWS offices with Hydrologic Service Area responsibility to issue adaptive forecasts at those points to better serve the public.

Although they do not have HSA responsibility, about 20 WSOs in the area impacted by The Great Flood of 1993 are responsible for issuing flash flood warnings for designated counties in their county warning areas. In addition, WSOs collect hydrologic data and serve as the local contact for the public and media and provide forecasts and warnings.

The offices with HSA responsibility and their areas of responsibility are delineated in Figure 6-2. A brief synopsis of the hydrologic features contained in each of the HSAs follows:

Bismarck (BIS): Rivers in North Dakota, including the Red River of the North main stem and tributaries in Minnesota from the Canadian border to the South Dakota border.

Chicago (LOT): Rivers in Illinois, including the main stem of the Mississippi from below Dubuque, Iowa, to below Dam 19 near Keokuk, Iowa, and the Calumet basin in northwest Indiana, except the main stem Ohio River along the Illinois-Kentucky border.

Des Moines (DMX):	Rivers in Iowa, including the main stem of the Des Moines River along the Iowa-Missouri border, except the main stem Mississippi River along the Iowa-Wisconsin-Illinois borders, except the main stem Missouri River along the Iowa-Nebraska border, and except the Big Sioux along the South Dakota-Iowa border.
Milwaukee (MKE):	The Montreal, Brule, and Menominee Rivers along the Michigan-Wisconsin border, and all streams in Wisconsin, except the St. Croix River along the Wisconsin-Minnesota border and except the Mississippi River along the Wisconsin-Minnesota border.
Minneapolis (MSP):	The St. Croix River along the Minnesota-Wisconsin border; the Mississippi River, to and including Dubuque, Iowa, and all rivers in Minnesota, except the Red River of the North main stem and tributaries.
Omaha (OMA):	Rivers in Nebraska, including the main stem Missouri River along the Nebraska-Iowa-South Dakota-Missouri borders.
Sioux Falls (FSD):	Rivers in South Dakota, including the Big Sioux along the South Dakota-Iowa border, except the main stem Missouri River along the South Dakota-Nebraska border.
St. Louis (LSX):	Rivers in Missouri; the Mississippi River from below Dam 19 near Keokuk, Iowa, to and including Caruthersville, Missouri; the Missouri River from the Missouri-Kansas border to the confluence with the Mississippi River; and the Ohio River from Cairo, Illinois, to its mouth. (Kansas City WFO has forecast responsibility for eight forecast points on the reach of the Blue River that flows through the Kansas City metropolitan area.)
Topeka (TOP):	Rivers in Kansas, except the main stem Missouri River along the Kansas-Missouri border.

6.4 HYDROLOGIC SERVICES FOR THE UPPER MISSISSIPPI RIVER BASIN

6.4.1 OVERVIEW OF FORECAST PRODUCTS

During The Great Flood of 1993, 189 locations within the NCRFC area of responsibility exceeded flood stage (41 percent of the total number of locations). Of these, 44 locations within the upper Mississippi River basin exceeded the previous flood of record. Appendix D lists locations and associated stage information for those stations which exceeded record crests.

Locations observing (preliminary) new record stages in the upper Mississippi River and Red River of the North basins, together with locations experiencing record and near-record stages in the Missouri River

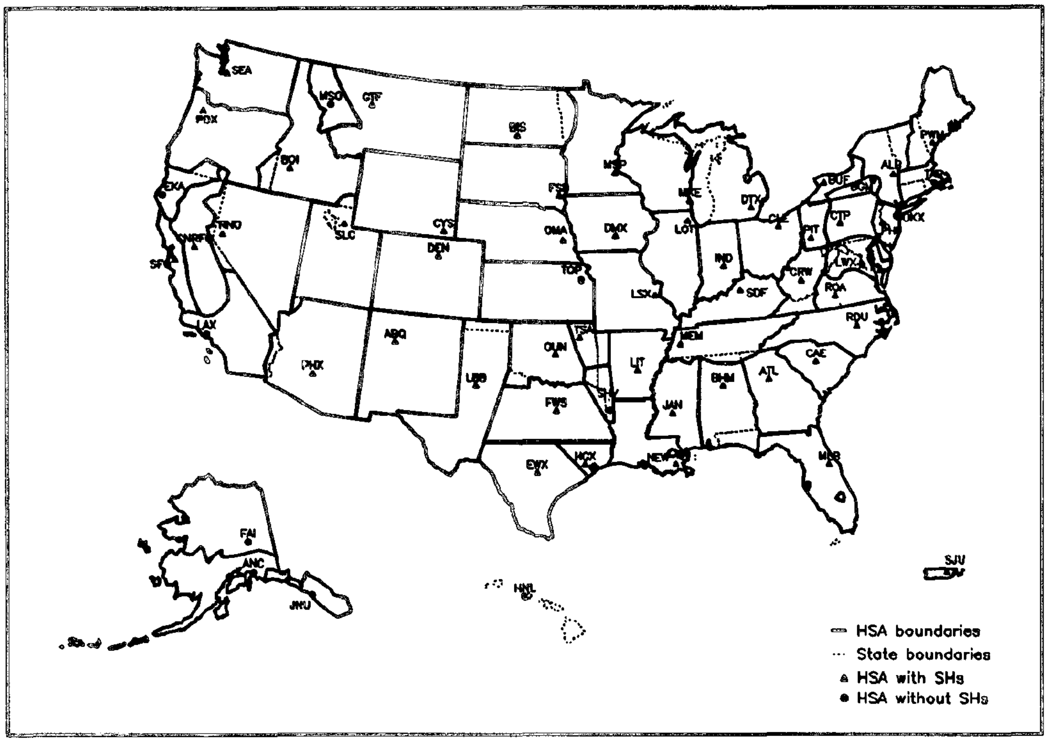


Figure 6-2. *Locations of, and areas served by, the NWS Offices with Hydrologic Service Area responsibilities.*

basin are shown in Figure 6-3. New record stages are indicated by filled triangles; gages that approached existing records are shown as filled circles. Numbers identifying each location correspond to the index numbers listed in the first column of Tables D-1 (new records in the Mississippi drainage: numbers 1-44), D-2 (new records in the Missouri drainage: numbers 45-93), D-3 (near records in the Missouri drainage: numbers 94-116), and D-4 (new records in the Red River of the North drainage: numbers 117-118).

HSA offices in Minneapolis, Chicago, Milwaukee, Des Moines and St. Louis issued thousands of hydrologic forecast and warning products during the flooding episode. Over 16,000 specific river forecasts[1] were issued for the upper Mississippi River basin during the event. Tables detailing products issued by each WSFO with HSA responsibility are included in Appendix E. Figure 6-4 shows the total number of these products issued during The Great Flood of 1993 by HSA offices. The same information, broken down chronologically, is shown in Figure 6-5. In this figure, each bar represents the total number of products issued by all HSA offices for each week, from June through mid-August.

[1] In many cases, a single product contained forecasts for multiple locations along one or more rivers. This accounts for the much larger number of specific forecasts than products issued.

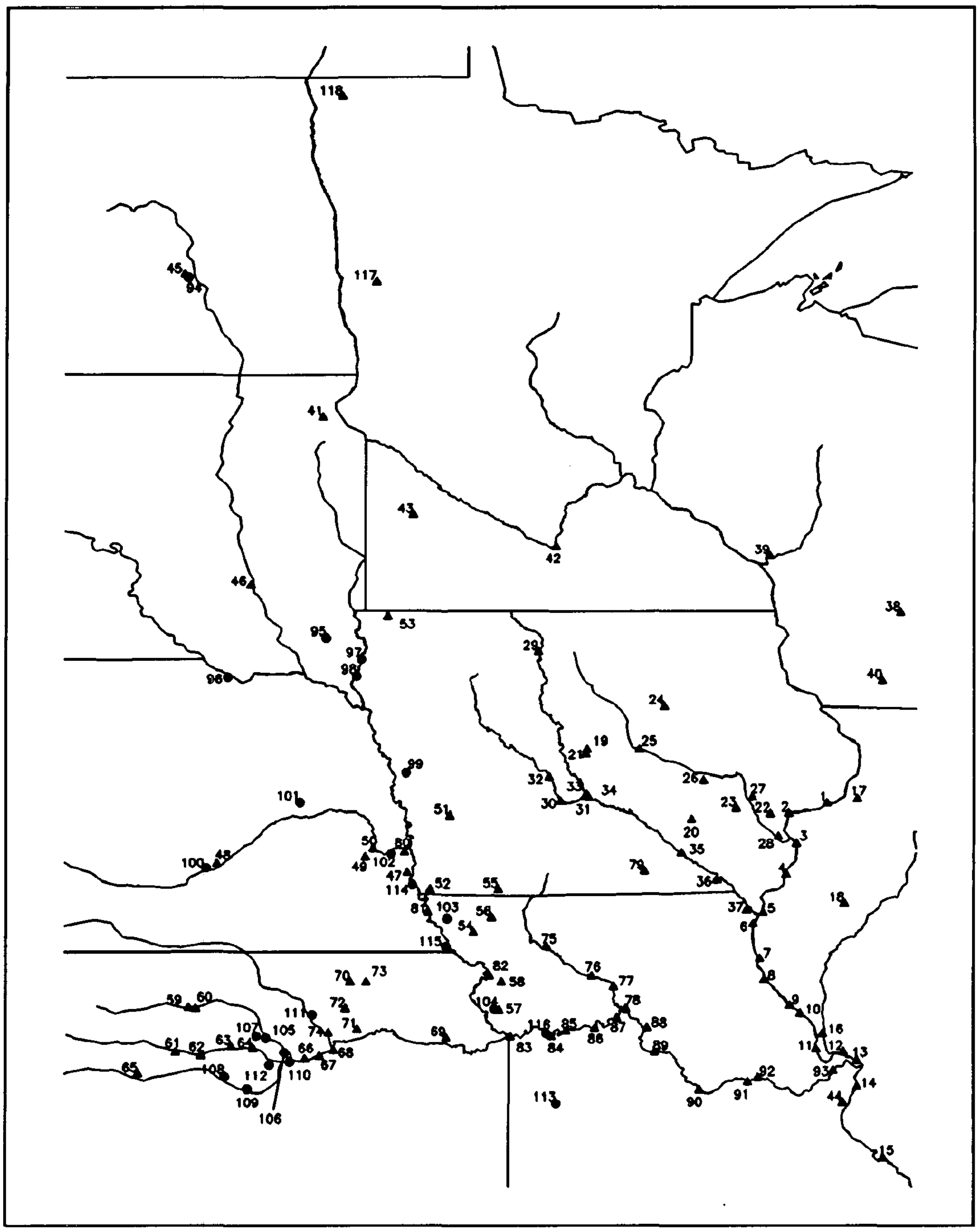


Figure 6-3. *Locations of (preliminary) record and, for the Missouri River basin, near-record river stages, during The Great Flood of 1993. The labels for each point correspond to index numbers listed in Appendix D. Triangles show new floods of record and circles are locations that approached the flood of record.*

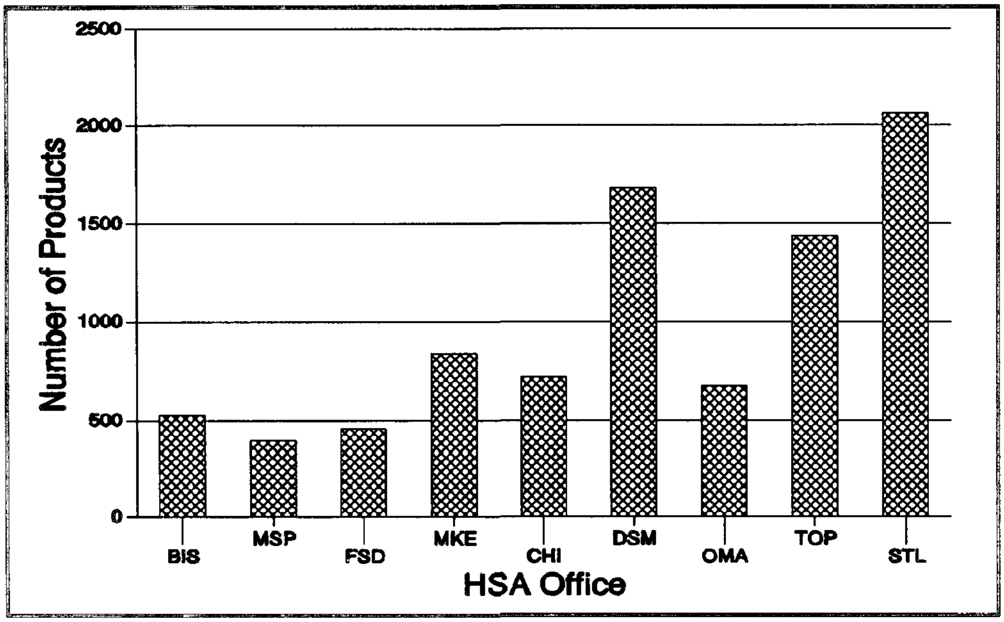


Figure 6-4. *Total number of products (forecasts, warnings, statements) issued by offices with HSA responsibility during The Great Flood of 1993. HSA IDs are listed in Table 6-1.*

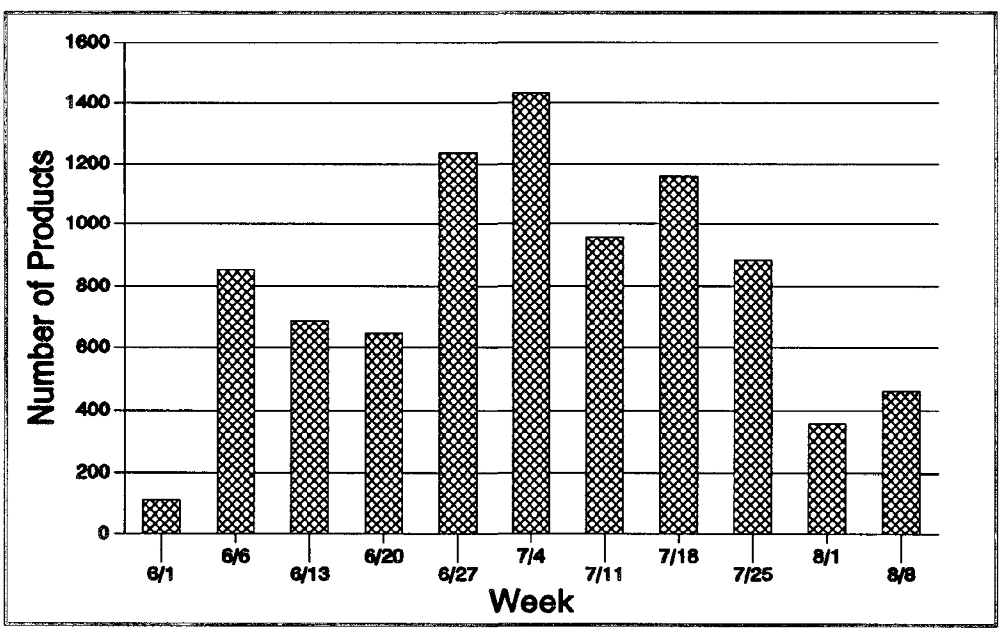


Figure 6-5. *Total number of products (forecasts, warnings, statements) issued each week by all offices with HSA responsibility during The Great Flood of 1993. HSA IDs are listed in Table 6-1.*

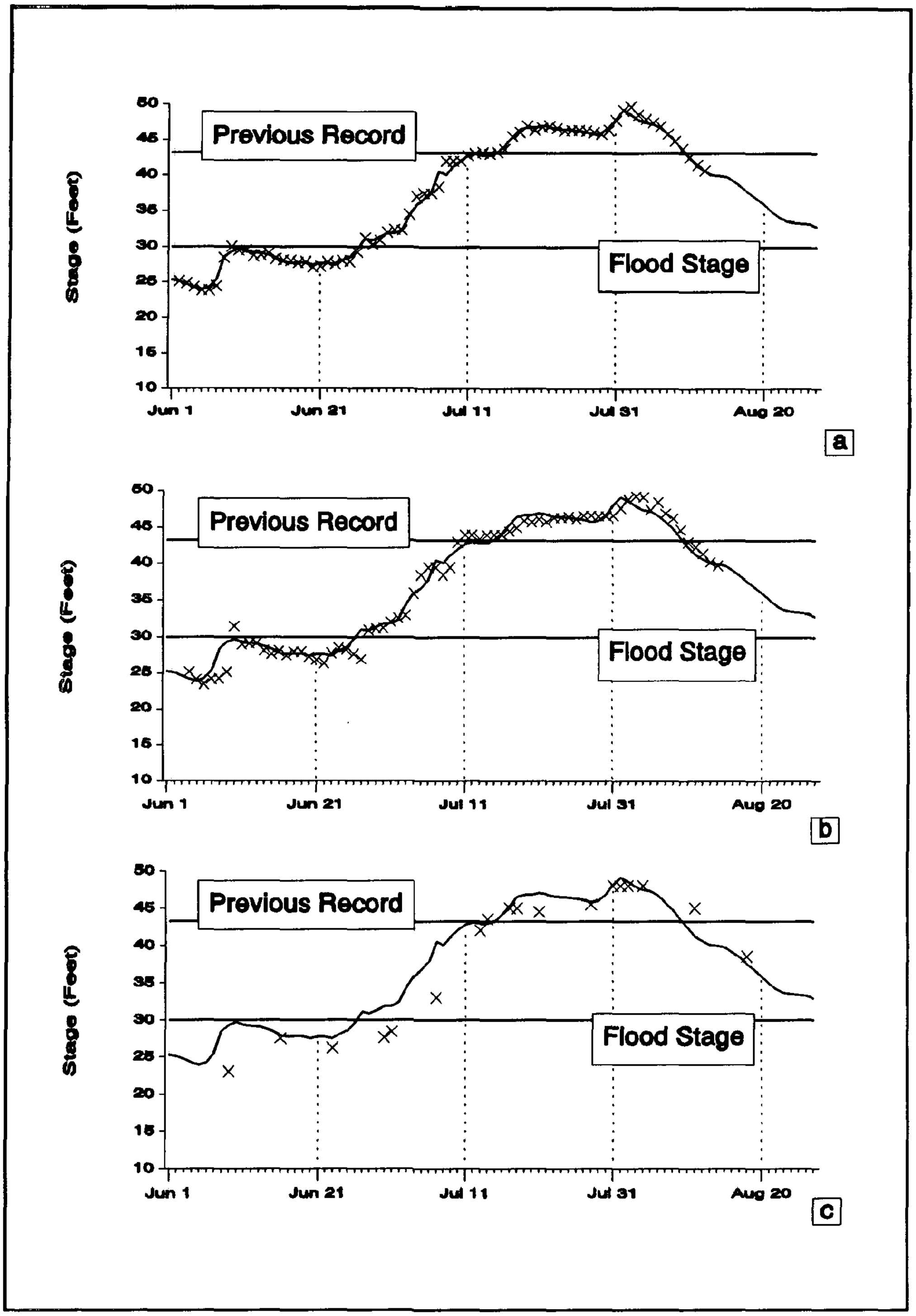


Figure 6-6. *St. Louis forecast (x) and observed (solid line) stages for: (a) 1 day, (b) 3 days, and (c) 7 days.*

6.4.2 ANALYSIS OF SELECTED HYDROLOGIC FORECASTS FOR THE UPPER MISSISSIPPI RIVER

The NCRFC makes routine hydrologic forecasts for 27 points along the main stem of the upper Mississippi River from Minneapolis, Minnesota, to Chester, Illinois. Every day, the RFC typically issues 3-day forecasts for each of the 27 forecast points. Every Wednesday, the RFC issues special long-term forecasts for 4, 5, 6, 7, 8, 9, 10, 12, 14, 21, and 28 days for 4 of the 27 points. The long-term forecasts are generated by special request from specific end-users, including the U.S. Army Corps of Engineers (COE) and the navigation industry. A principal use of the long-term forecasts by the navigation industry is to provide an estimate of low-flow conditions that could occur as much as 28 days in the future and that could consequently impact river barge traffic. It is possible to evaluate the skill of the forecasts by comparing them with the observed river stages at various forecast points along the main stem of the upper Mississippi River.

The NCRFC provided the survey team with forecasts and observed stage data for June, July, and August 1993 for many of the Mississippi River forecast points. A series of hydrographs was generated using the daily stage observations and the future forecasts for lead-times out to 28 days. Figures 6-6 and 6-7 show the stage observations along with the forecasts for specific dates during the summer as a function of selected lead-times for St. Louis. For example, Figure 6-6(a) gives the observed stage and forecast stage for each day. The forecast is plotted in the figure on the date for which it applies, i.e., the forecasts in Figure 6-6(a) were made 1 day earlier than the date on which they are plotted. In Figure 6-6(b), the forecasts were made by the RFC 3 days before the date on which they are plotted. Similarly, Figure 6-6(c) shows the 7-day forecast comparison. The flood stage and previous flood of record are also shown on the hydrographs. Figure 6-7 shows similar comparisons for 14-, 21- and 28-day forecasts.

Figures 6-6 and 6-7 graphically depict the skill associated with the forecast as a function of lead-time for the St. Louis forecast point. One should expect a degradation in skill as forecast lead-times extend into the future. A principal reason for the decreased skill with lead-time is associated with the fact that precipitation that falls after the forecasts are made is not accounted for in the forecast. Consequently, hydrologic forecasts tend to underforecast if significant, subsequent precipitation falls in the drainage area of the forecast point. A systematic underestimate or overestimate is referred to as "bias." This systematic underestimate, or bias, is clearly shown in Figure 6-7 that gives hydrographs with longer forecast times. The 28-day hydrologic forecasts for the St. Louis forecast point (Figure 6-7(c)) tend to severely underestimate the observed stage because of the massive amount of precipitation that fell after the forecasts were made.

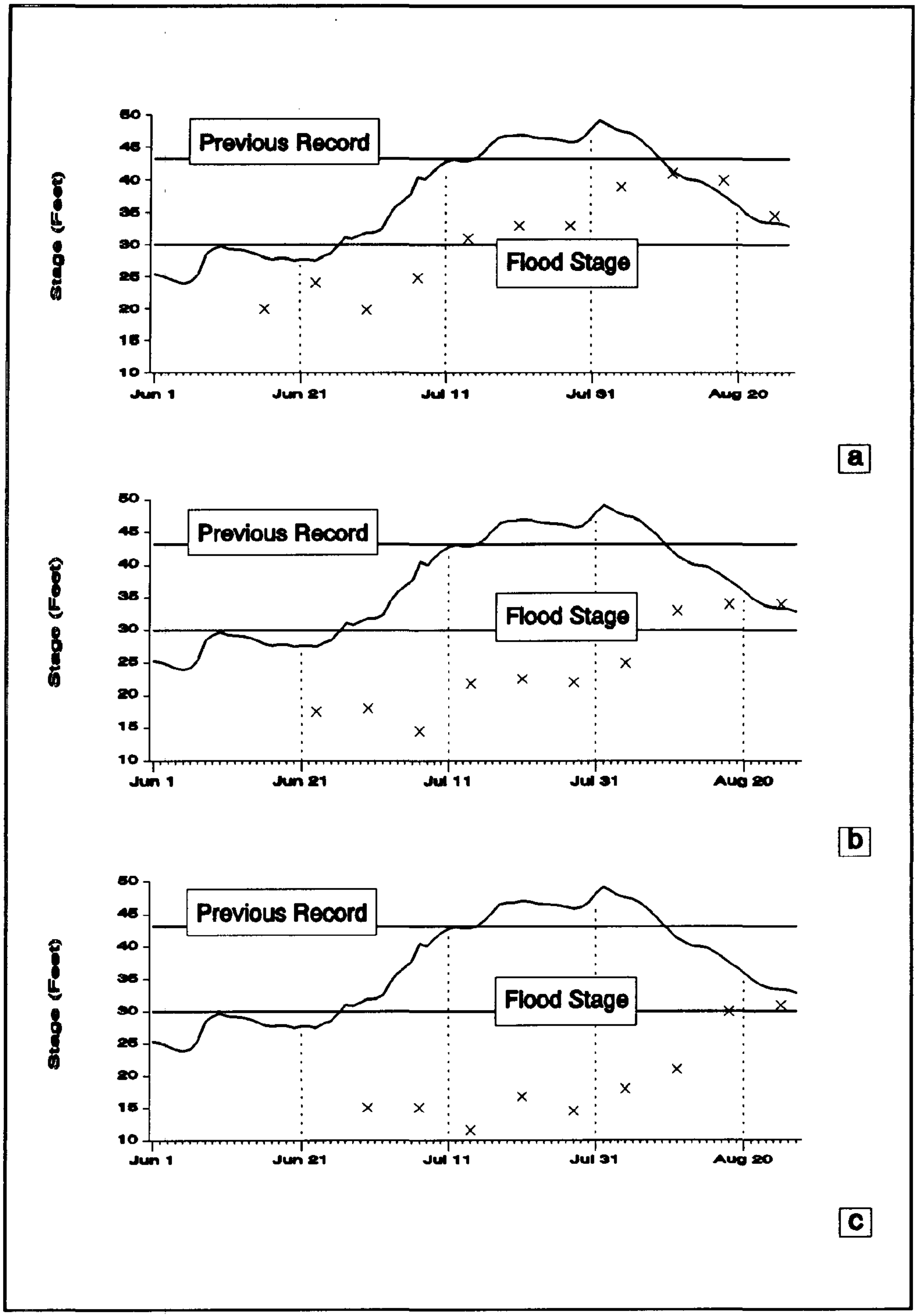


Figure 6-7. *St. Louis forecast (x) and observed (solid line) stages for: (a) 14 days, (b) 21 days, and (c) 28 days.*

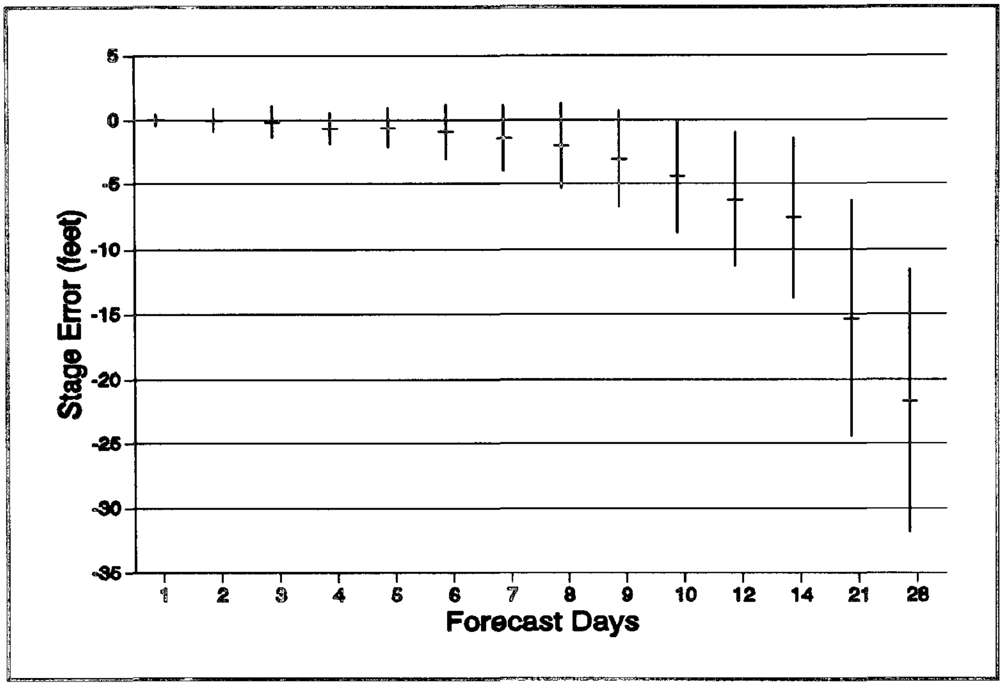


Figure 6-8. *Bias and associated error for each forecast duration at St. Louis.*

In addition to the tendency to systematically underforecast the future river stage (bias) during periods of extended precipitation, there is also a tendency for the forecast errors to increase in major flood events. Uncertainties associated with rating curve shifts, channel scour and fill, possible levee overtopping, and observed precipitation estimates can cause major errors in long-term forecasts. Figure 6-8 depicts the bias and error associated with the river forecasts for the St. Louis forecast point as a function of lead-time, or forecast days. The bias for the June-July forecast period was calculated as the average of the forecast minus observed river stage for each day in which there was a forecast. The error was calculated as the standard deviation of the forecast minus observed river stages. For example, in Figure 6-8, the bias and error for 1 forecast day at St. Louis are 0.02 and 0.50 foot, respectively. The bias and error for forecasts made out to 28 days increases dramatically, for a variety of reasons, to -21.67 and 10.17 feet, respectively. Figure 6-8 clearly shows that forecast bias and error increase dramatically with forecast lead-time.

A similar analysis was completed for the Mississippi River at Chester, Illinois, and is presented in Appendix F. The bias and errors of the long-term forecasts at Chester are summarized in Figure 6-9. The increase in both bias and forecast error with increasing forecast duration is generally similar to that shown for St. Louis in Figure 6-8.

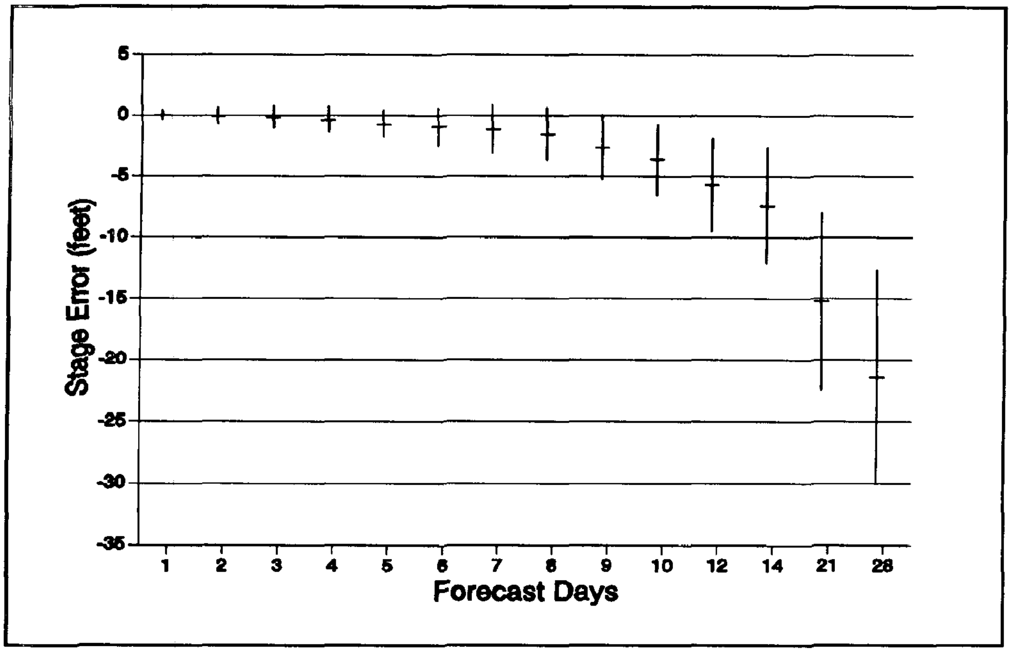


Figure 6-9. *Bias and associated error for each forecast duration at Chester, Illinois.*

In addition to analyzing forecast accuracy as a function of lead-time, it is also possible to look at accuracy as a function of the upstream-downstream location of the forecast point in the river system. The NCRFC makes 3-day forecasts each day for a number of forecast points along the upper Mississippi River. There were eight forecast points selected for error analysis. They are, in downstream order, St. Paul (STP), LaCrosse (LAC), Guttenburg (GUT), Burlington (BUR), Dam 24 (D24), Grafton (GRF), St. Louis (STL), and Chester (CHS). Figure 6-10 gives the Mississippi River forecast biases and errors for the 3-day forecasts for the aforementioned forecast points. The biases and errors are plotted in the figure for each of the forecast days (1 through 3) and each of the forecast points in downstream order. For example, STP refers to the St. Paul bias and error and the figure shows the 1-day forecast, 2-day forecast, and 3-day forecasts in left-to-right order. Again, expected patterns emerge. Biases and errors increase with forecast lead-times. A common pattern shows a decrease in forecast error for any fixed forecast lead-time in a downstream direction, e.g., STP-LAC-GUT. This pattern, however, can be broken by the contribution of significant flows from tributary streams. Figure 6-10 certainly shows this effect from the Mississippi tributary inflows in Iowa, Illinois, and, ultimately, the Missouri River for the St. Louis forecast. The St. Louis 3-day forecast shows the greatest forecast error with a bias of -0.13 and an error of 1.24 feet.

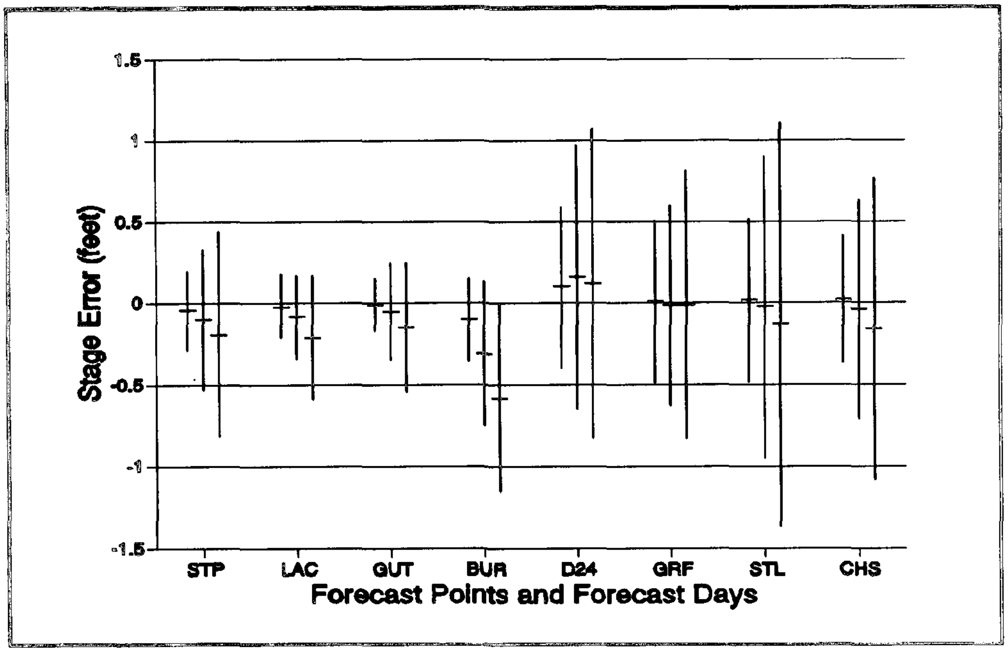


Figure 6-10. *Mississippi River forecast errors.*

6.5 HYDROLOGIC SERVICES FOR THE MISSOURI RIVER BASIN

6.5.1 OVERVIEW OF FORECAST PRODUCTS

During The Great Flood of 1993, 211 locations within the MBRFC area of responsibility were at levels that exceeded flood stage (47 percent of the total number of locations). Of these, 49 locations exceeded the flood of record while stages at 24 locations crested near the flood of record. Appendix D gives a list of locations and associated stage information for those stations which exceeded or approached record crests in the Missouri River basin. Figure 6-3 shows the locations of these points.

HSA offices in Bismarck, Sioux Falls, Omaha, Des Moines, Topeka, and St. Louis issued thousands of hydrologic forecast and warning products to cover the flooding episode. Tables detailing products issued by each WSFO with HSA responsibility are included in Appendix E. Figures 6-4 and 6-5 show the distribution of these products by HSA office and over time during The Great Flood of 1993.

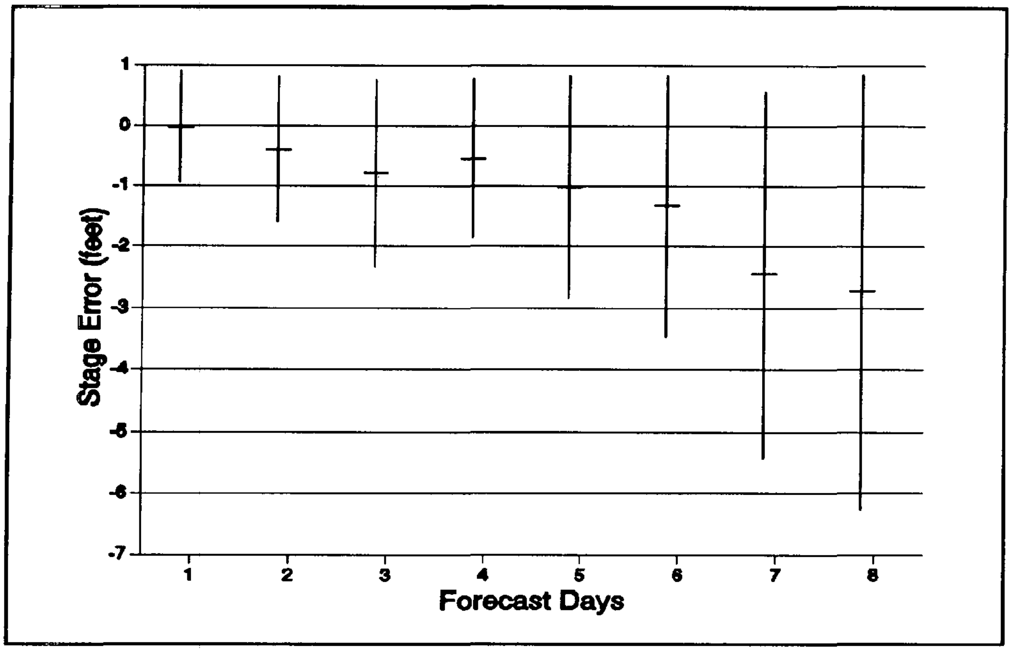


Figure 6-11. *Bias and associated error for each forecast duration at Sioux City, Iowa.*

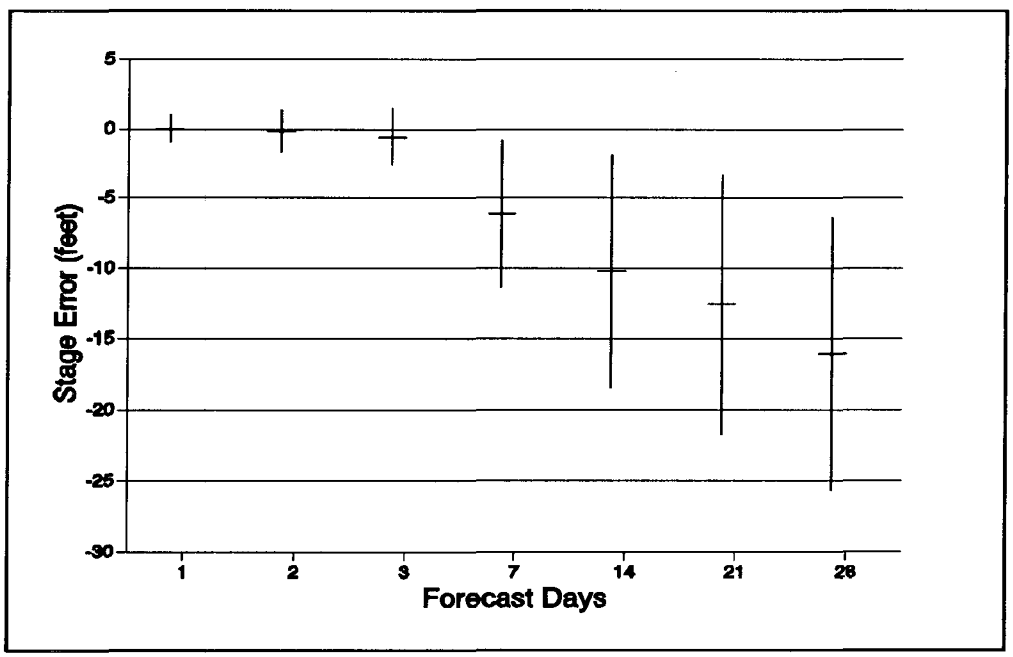


Figure 6-12. *Bias and associated error for each forecast duration at Boonville, Missouri.*

6.5.2 ANALYSIS OF SELECTED HYDROLOGIC FORECASTS FOR THE MISSOURI RIVER

The MBRFC makes hydrologic forecasts for 21 forecast points along the Missouri River from Sioux City, Iowa, down to St. Charles, Missouri. Of these 21 points, 9 have forecasts issued for them only when they are in flood (crest forecasts). Each day, the RFC makes routine 3-day forecasts for the other 12 forecast points. Additionally, the RFC issues daily extended 4-, 5-, 6-, and 7-day forecasts for 2 of the 12 forecast points. Each Wednesday, the RFC issues extended forecasts for days 4, 5, 6, 7, and 8 for 4 of the 12 forecast points, and 4-week extended forecasts for days 7, 14, 21, and 28 for 7 of the 12 forecast points. The long-term forecasts are generated by special request from specific end-users including the COE and the navigation industry. A principal use of the long-term forecasts by the navigation industry is to provide an estimate of low-flow conditions that could occur as much as 28 days in the future and that could consequently impact river barge traffic. It is possible to evaluate the skill of the forecast by comparing the forecasts with the observed river stages at various forecast points along the main stem of the lower Missouri River.

Long-term forecasts (7, 14, 21, and 28 days) are issued by the MBRFC for the following seven forecast points: Omaha and Rulo, Nebraska; and St. Joseph, Kansas City, Boonville, Jefferson City, and Hermann, Missouri. The Sioux City, Iowa, forecast point and the Boonville and Hermann, Missouri, forecast sites were selected for further analyses. The RFC issues forecasts for Sioux City 8 days into the future and for the Boonville and Hermann sites 7, 14, 21, and 28 days into the future. A series of hydrographs was generated using the daily stage observations and the future forecasts for each of the aforementioned forecast lead-times. Results for these sites, similar to those shown for St. Louis in Section 6.4.2, are presented in Appendix F.

As with St. Louis, the skill associated with these forecasts drops off as forecast lead-times extend into the future. A principal reason for the decreased skill with lead-time is associated with the fact that precipitation that falls after the predictions are made is not accounted for in the forecast. Consequently, hydrologic forecasts tend to underforecast if significant, subsequent precipitation falls in the drainage area above the forecast point. This systematic underestimate is most clearly evident for longer forecast times.

Figures 6-11, 6-12, and 6-13 depict the bias and error associated with the river forecasts for the Sioux City, Boonville, and Hermann forecast points, respectively, as a function of lead-time, or forecast days. Each figure gives both the bias and the associated error for each of the forecast durations. The bias for the June-August forecast period was calculated as the mean of the forecast minus observed river stage for each day in which there was a forecast. The error was calculated as the standard deviation of the forecast minus observed river stages. For example, in Figure 6-13, the bias and error for the 1-day forecast at Hermann are -0.21 and 1.30 feet, respectively. The bias and error for forecasts made out to 28 days increases dramatically, for a variety of reasons, to -16.68 and 8.58 feet, respectively. Figures 6-11, 6-12, and 6-13 clearly show that forecast bias and error increase with forecast lead-time.

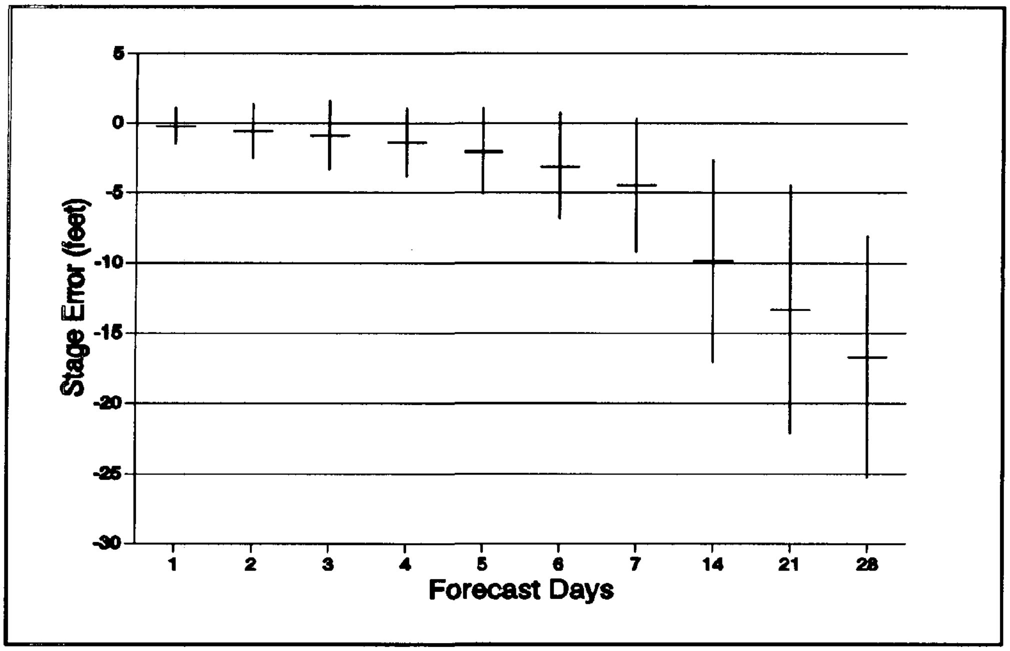


Figure 6-13. *Bias and associated error for each forecast duration at Hermann, Missouri.*

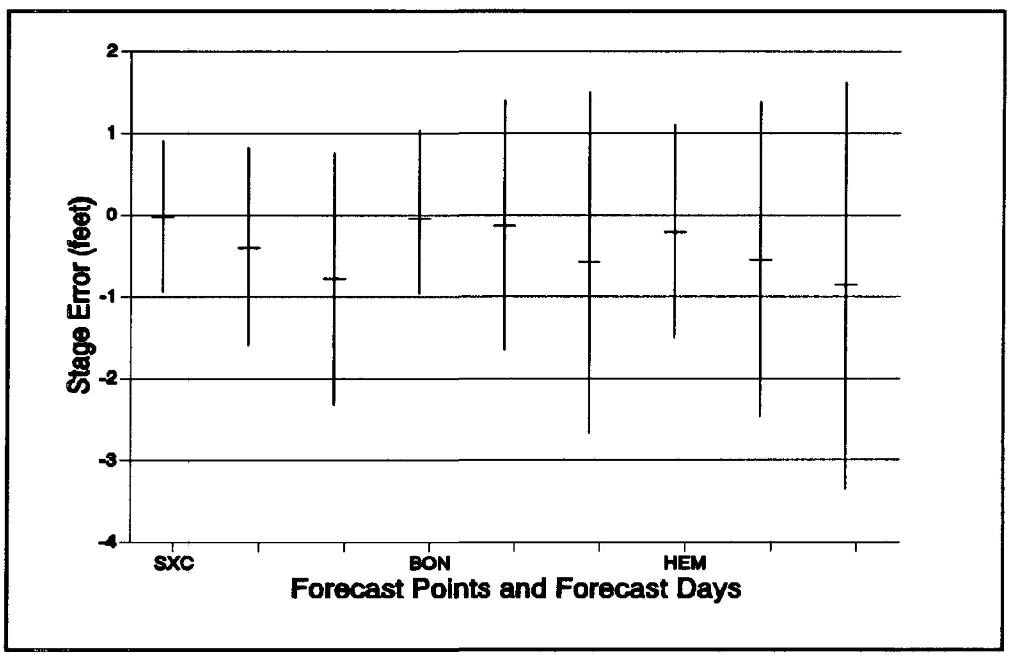


Figure 6-14. *Missouri River forecast errors.*

In addition to analyzing forecast accuracy as a function of lead-time, it is also possible to look at accuracy as a function of the upstream-downstream location of the forecast point in the river system. The MBRFC makes 3-day forecasts each day for a number of points along the Missouri River. There were three forecast points selected for error analysis. They are, in downstream order, Sioux City (SXC), Boonville (BON), and Hermann (HEM). Figure 6-14 gives the Missouri River forecast biases and errors for the 3-day forecasts for the aforementioned forecast points. The biases and errors are plotted in the figure for each of the forecast days (1 through 3) and each of the forecast points in downstream order. For example, SXC refers to the Sioux City bias and error and and the figure shows the 1-day forecast, 2-day forecast, and 3-day forecasts in left-to-right order. Again, expected patterns emerge, e.g., biases and errors increase with forecast lead-times. The Hermann 3-day forecast shows the greatest forecast bias of -0.86 and error of 2.49 feet.

6.6 HYDROLOGIC SERVICES FOR THE RED RIVER OF THE NORTH

6.6.1 OVERVIEW OF FORECAST PRODUCTS

During the flood, 2 of 44 locations in the Red River of the North basin exceeded the flood of record. Hundreds of river forecasts were issued. Appendix D gives the locations and associated stage information for the two stations which exceeded record crests in the Red River of the North. They are also shown in Figure 6-3.

A table detailing the various forecast products issued by the WSFO Bismarck is included in Appendix E, and the products are included in Figures 6-4 and 6-5. There was excellent cooperation between Environment Canada in Winnipeg and WSFO Bismarck in the exchange of crucial hydrologic information. WSO Fargo also answered hundreds of inquiries and provided service support at the local level.

6.7 RIVER FORECASTS AND USE OF PREDICTED PRECIPITATION

It is obvious from examining Figures 6-8 through 6-14 that the magnitude of the errors in the river forecast dramatically increase with increasing forecast lead-time. The predominant factor (during periods with substantial rainfall) responsible for this trend is the inability to effectively forecast and incorporate estimates of future precipitation into the current river forecast procedures. There are two main impediments: (1) the forecast system does not readily lend itself to the incorporation of precipitation forecast information, and (2) the current state of the art in precipitation forecasting produces forecasts that do not provide the level of precision needed by current hydrologic modeling techniques.

As indicated in Chapter 4, current hydrologic models used to prepare river forecasts are "lumped parameter" models that assume uniform precipitation over each subbasin. Quantitative Precipitation Forecasts (QPF) provide estimates of 24-hour precipitation amounts for 1 and 2 days into the future; categorical or probabilistic forecasts/outlooks are available for longer lead-times. To incorporate this information into river forecasts, the area covered by each subbasin (both the NCRFC and the MBRFC make calculations for approximately 750 subbasins each) must be identified on the maps showing the QPF estimates. It is not possible to do this digitally within the framework of the existing NCRFC and MBRFC forecasting systems or with the current limitations in the nondigital format of the QPF products currently distributed by the National Meteorological Center (NMC). Efforts are currently underway at NMC, within the NWS Eastern Region, and at the Arkansas-Red Basin RFC (ABRFC) to develop efficient techniques to incorporate QPF digitally as input to RFC forecast operations.

Even when digital QPF information becomes available to the RFCs, however, there are still significant, technical issues that must be overcome before QPF can be used objectively and quantitatively in routine forecast preparation (see Appendix B). While QPF shows a high level of skill on the synoptic scale[2], it cannot yet precisely define precipitation amounts at the subbasin scales needed in the current forecast system. The case study that follows in Section 6.9.1 gives an indication of how inaccurate precipitation information can cause significant errors in the river forecasts. Nevertheless, it is clear that, with improved methodology to couple QPF information effectively with advanced hydrologic modeling approaches, improvements can be achieved in hydrologic forecasts even with the current QPF skill levels.

Clearly, progress will require applied research and development focused on both improving the accuracy at the smallest scales in the QPF forecasts, as well as innovative techniques to extract the maximum amount of information contained in the QPFs. At the subbasin scale, there is a low "signal-to-noise ratio" in current QPF forecasts. Research to reduce the "noise" (or random forecast error) in the QPF estimates at this scale is needed. However, aggregation of the QPF information to larger scales, which improves accuracies, provides promise for subsequent "disaggregation" when coupled with appropriate, advanced hydrologic modeling techniques. It is likely that probabilistic techniques, such as Extended Streamflow Prediction[3] methodology, can play an integral role in developing schemes to better use QPF. The ultimate solution will require the close collaboration of both those providing QPFs and the RFCs who can become one of the most important end-users. The Hydrometeorological Analysis and Support (HAS) function at the RFCs in the modernized weather service will be critical to providing an effective bridge between the RFCs and producers of QPFs at the WFOs and at NMC.

---

[2] A synoptic scale feature is one comparable in size to a mature, winter cyclone, or 600-1,000 miles across.

[3] Day, Gerald N., and Edward J. VanBlargan. 1983. The use of hydrometeorological data in the NWS Extended Streamflow Prediction program. **Fifth Conf. Hydromet.**, Tulsa, Oklahoma, American Meteorological Society.

<u>FINDING 6.1:</u> Long-term river forecasts significantly underestimated stages because they did not include estimates of future precipitation.	<u>RECOMMENDATION 6.1:</u> Information contained in precipitation forecasts and outlooks must be factored into river forecasts.
<u>FINDING 6.2:</u> Current precipitation forecasts are not available in a format that allows easy incorporation into operational river forecast procedures.	<u>RECOMMENDATION 6.2:</u> Manually prepared precipitation forecasts and outlooks must be formatted to allow for the efficient, automated incorporation of digital precipitation forecasts into river forecast procedures.
<u>FINDING 6.3:</u> Precipitation forecasts are least accurate at the smaller scales required by current hydrologic forecast procedures. Nevertheless, QPF information at current skill levels contains valuable information that could benefit hydrologic modeling.	<u>RECOMMENDATION 6.3:</u> The NWS must focus efforts to: (1) enhance precipitation forecasting on the space and time scales needed in hydrologic models and (2) develop methodology that incorporates QPF information into advanced hydrologic modeling approaches.
<u>FINDING 6.4:</u> Extended Streamflow Prediction techniques provide a promising framework to incorporate precipitation forecasts into the hydrologic modeling and forecast system.	<u>RECOMMENDATION 6.4:</u> The NWS should support research, development, and operational testing to incorporate current QPF and other precipitation outlooks into river forecasting procedures.
<u>FINDING 6.5:</u> Effective integration of QPF information into hydrologic models is extremely difficult and will require close collaboration between NMC and the RFCs.	<u>RECOMMENDATION 6.5:</u> An exchange program should be instituted whereby RFC staff visit NMC and NMC staff visit various RFCs to address the technical and scientific problems preventing effective use of QPF in operational river forecast models.

6.8 GENERAL ANALYSIS OF FORECAST AND WARNING SERVICES

More than ten thousand forecast statements and warning products were issued by NWS field offices during The Great Flood of 1993. By and large, these products were well-worded and provided many beneficial details to the media, public, government agencies, and other specialized users, such as the private hydrometeorological community. As stated in the introduction, a general finding is that the NWS, given the size of the event and the constraints of aging technologies, provided outstanding forecast and warning services. During the entire event, NWS employees went far beyond the call of duty to provide lifesaving and property-saving hydrologic products to the public and other agencies. As is the case with any event of this magnitude, operational problems surfaced.

The NWS is the Federal agency charged with the responsibility for issuing weather and river forecasts and warnings to the public. Additionally, the NWS provides forecasts to other agencies, principally its major cooperators, such as the COE. The COE regulates more than 700 major projects congressionally authorized for multiple-purpose flood control, navigation, hydropower, and recreation. In addition to the major reservoir projects, the COE has constructed hundreds of levees across the Nation. Timely NWS forecasts and warnings of river stages are an essential part of the COE operation. On a regular basis, the NWS provides meteorological and hydrological information and forecasts to the COE, while the COE provides hydrological information, forecasts, and facility operations schedules to the NWS. The Great Flood of 1993 mandated an exchange of information between the two agencies of incredible magnitude and frequency.

Although the COE uses NWS hydrologic forecasts to accomplish its basic mission in water control management of the Federal projects under its control, in-house hydrologic forecasts are prepared by the COE during flood events for internal use only. The COE forecasts are made for reservoir inflows and for various locations on rivers and streams where the NWS may or may not issue an official forecast.

The COE and the NWS experienced excellent cooperation during the initial phases of The Great Flood of 1993. There were numerous reports on the timely information exchange between the two agencies. As the event continued, however, some philosophical differences began to emerge. The considerable drain on human resources and the intense media pressure associated with The Great Flood of 1993 highlighted the basic differences in the missions and the role of hydrologic forecasts within the COE and the NWS.

The NWS issues forecasts and warnings to prevent the loss of life and property damage. Based on NWS forecasts, the public can take appropriate action. The COE, however, uses its reservoir inflow forecast for modeling and operation of its major reservoirs. The COE is also responsible for maintaining the safety of the public from failed or overtopped levees. This latter requirement mandates a certain "safety factor" and creates a tendency for the COE to prefer forecasts on the "high" side to permit adequate time to raise tops of levees to prevent overtopping. The high estimates were in evidence in the COE's in-house forecasting during the last phases of The Great Flood of 1993 when many levees either failed or were overtopped. When comparing forecasts with the COE during the early to middle portions of The Great Flood of 1993, there was general agreement. The high-side forecasts became apparent, however, at the time of the extreme flow on the Mississippi River at St. Louis.

A concern expressed not only by users but also by NWS meteorological forecasters is that there are too many types of products. Meteorologists and hydrologists occasionally had difficulty in deciding which products to issue. Some users were not familiar with certain products or how to interpret them. There were suggestions that warnings, forecasts, and other information may need to be repackaged. Also, there was inconsistency among certain offices, in some instances, on the type of product issued to cover a particular hydrometeorological situation.

Many NWS field managers and forecasters expressed the need for objective means to evaluate the overall flood prediction capability of the NWS. They felt that it is essential to have a procedure to critique significant flood events for self-evaluation and professional development and to indicate the effectiveness of future enhancements to the hydrologic forecast program. Although NWS presently has a nationwide verification program for severe weather and other weather programs, there is no systematic evaluation of how well the NWS does in its national flood forecasting service. An effort involving the West Gulf RFC (WGRFC), other selected field offices, and the Office of Hydrology has led to the design of a national verification system for river forecasts; it has not yet been implemented.

Several items surfaced concerning the National Oceanic and Atmospheric Administration (NOAA) Weather Radio (NWR). In some offices, issue dates and times were not always broadcast with forecasts and observed stage data. Listeners were sometimes confused about the latest information, especially during periods of rapidly changing stages. Gaps in NWS coverage are an ongoing problem. The WSFO in Sioux Falls expressed concern about not having NWR coverage for a large recreational area along the Missouri River.

The lack of adequate staffing, and the effect that it may have had on providing high-quality forecast and warning services, was noted both at RFCs and HSA offices. Overtime use was extensive. Many offices had employees out for extended training, and other employees were on summer leave. HSA offices and RFCs reported receiving thousands of telephone calls--sometimes hundreds a day--from the public and the media. All offices indicated that they did not have enough staff to handle the extra workload. There was a period of about 2 weeks when the network radar at St. Louis experienced numerous outages. During this period, the staff at WSO Columbia was required to provide backup support from the Columbia local warning radar. WSO Columbia normally operates with just one person each shift. One RFC and several HSA offices used NWS personnel temporarily detailed from other NWS offices. This helped to alleviate some, but not all, of the workload problems.

One major complaint, voiced by some emergency managers and other Federal offices, was that the NWS did not have a full-time, or at least routine, local presence at emergency operations centers that were established in several areas. One effect of this was that the NWS was not always given credit for its forecast and warning services. The WSFO in Des Moines and the NCRFC did provide representatives for extended periods on several occasions at local operations centers. This was extremely beneficial to improved coordination and dissemination of information and to the visibility of NOAA/NWS services.

Another issue related to staffing is the lack of a Service Hydrologist (SH) at an HSA office. Many meteorological forecasters did not feel proficient handling prolonged and major hydrologic operations when an SH was not in the office or on staff. During major portions of the flood event, continuing 24-hour operations at the RFCs would have been very helpful. The WSFO in Topeka and Minneapolis expressed a concern that it is very difficult to maintain a high-quality hydrologic program without immediate, local access to specialized expertise. The corollary is that offices with SH positions stated they were indispensable in their capacity as local experts who coordinated training, data flow, user interaction, media contacts, and forecast service. During the flood event, the SHs were uniformly innovative and resourceful in their efforts to amass valuable hydrometeorological data to support the NWS hydrologic forecast and warning programs. They frequently developed and maintained local contacts necessary to ensure NWS access to data sets collected by a wide variety of Federal, state, and local hydrometeorological data collection networks.

Inaccuracy or delay in the forecast is felt sharply at the HSA offices. On some occasions, RFC forecasts were outdated by the time they were received at the WSFOs. These occasions put heavy demands on the skill of WSFO forecasters in handling hydrologic operations and on the RFC/WSFO coordination process. Planned improvements in the forecast update cycle through NWS modernization will alleviate many of these problems, but issues must also be dealt with as effectively as possible now and throughout the transition to modernized operations.

FINDING 6.6: WSFOs and WSOs exhibited a wide range of philosophies in the issuance of warnings versus statements. The decision of what type of product to issue can become a judgment call. To some degree, it is based on the geographical area and associated flood climatology.	RECOMMENDATION 6.6: All offices should review Weather Service Operations Manual chapters that describe types and content of products and adhere to these guidelines as closely as possible. The Regional Hydrologist should coordinate with the SHs to ensure consistent use of products (see Recommendation 6.17).
FINDING 6.7: No systematic, national program exists to verify river forecasts.	RECOMMENDATION 6.7: WGRFC, other participating field focal points, and the Office of Hydrology have designed an appropriate national verification system. These offices should continue development and implementation of the procedures and software required for the system.

<u>**FINDING 6.8:**</u> A growing recreational area along the Missouri River south of Sioux Falls often draws as many as 100,000 campers. There is no way to provide weather information to these campers.	<u>**RECOMMENDATION 6.8:**</u> The NWS should provide an NWR repeater in or near the recreational area.
<u>**FINDING 6.9:**</u> WSFOs and RFCs were inadequately staffed to manage a disaster of this magnitude. In the few locations where extra personnel were imported from NWS offices that were not currently experiencing severe hydrologic problems, impacts were always positive.	<u>**RECOMMENDATION 6.9:**</u> Each region should establish a personnel back-up procedure for large, protracted events.
<u>**FINDING 6.10:**</u> WSO Columbia staff was required to provide radar backup when the WSFO St. Louis' WSR-57 Network Radar was down. This created an additional burden on the already over-worked staff. This problem will be slowly resolved when WSR-88D radars begin to be commissioned.	<u>**RECOMMENDATION 6.10:**</u> Every effort should be made to reach acceptable operational availability levels for commissioning WSR-88D radars as soon as possible.
<u>**FINDING 6.11:**</u> Many meteorological forecasters did not feel proficient handling prolonged and major hydrologic operations when an SH was not in the office or on staff. WSFO Topeka has no SH. Consequently, it was much more difficult to maintain a high-quality hydrologic program without immediate access to specialized hydrologic expertise. Those offices with SH positions reported them indispensable in the capacity of local expert who coordinates hydrologic training of office staff, data flow, user interaction, media contacts, and forecast services.	<u>**RECOMMENDATION 6.11:**</u> In the modernized weather service, the NWS should revisit its planned staffing allocations for SHs necessary to support those WFOs that have high levels of significant hydrologic activity.

FINDING 6.12: The SHs served as the primary contacts at the WSFOs to accumulate a wide variety of data from a large number of hydrometeorological data networks supported by numerous Federal, state, and local agencies. The SHs were creative and innovative in their efforts to ensure that critical hydrometeorological data were available for use in the NWS hydrologic forecast and warning program.	**RECOMMENDATION 6.12:** See Recommendation 6.11.
FINDING 6.13: Both MBRFC and NCRFC provided extended coverage for most of the protracted flood event on a 7-days-a-week schedule well into the evening (usually until 10 or 11 p.m.). Nevertheless, certain users cited an inability to acquire needed information during hours when the RFCs were not in operation, and many end-users require 24-hour RFC support during major flood events. The NCRFC provided around-the-clock coverage for 4 days during the event. The MBRFC provided 24-hour coverage for 2 days.	**RECOMMENDATION 6.13:** RFCs should be staffed for 24-hour coverage during major flood events.
FINDING 6.14: By the time some RFC forecasts were received by the WSFOs, observed river stages exceeded forecast stages. As the modernization process improves the timeliness of the forecast cycle, improves the forecast accuracy, and reduces product transmission delays, the frequency of this type of occurrence will be reduced.	**RECOMMENDATION 6.14:** Whenever RFC forecasts are obviously in error, WSFO forecasters should immediately coordinate with the supporting RFC before issuing any public product based on these forecasts.
FINDING 6.15: The NCRFC staff stated that if the planned staffing for HAS forecasters in the modernized weather service had been on board, the NCRFC would have been able to analyze, in greater depth, the radar rainfall estimates and QPF products.	**RECOMMENDATION 6.15:** Within the current budget constraints, NWS Headquarters and regional offices should do everything possible to complete the modernized staffing levels for the RFCs.

<u>FINDING 6.16:</u> There were end-users that did not have access to and/or the expertise required to interpret the voluminous amounts of information contained in the large number of NWS products. This potentially can become an even greater problem in the modernized NWS when much more site-specific information becomes available.	<u>RECOMMENDATION 6.16:</u> It is critical that the packaging and distillation of the relevant information for water control and emergency management decision makers be improved. Some of this problem may subside as the NWS moves into modernized methods of providing information in graphical format. Until then, HSA offices and RFCs should contact their principal governmental users to discuss and implement innovative packaging of information tailored to their local areas and needs.
<u>FINDING 6.17:</u> During the flood event, a large number of flood products were issued including Flood Warnings, Flash Flood Warnings, and Urban and Small Stream Flood Advisories. The appropriate choice of product headers, and when to use them, at times confused NWS meteorological forecasters.	<u>RECOMMENDATION 6.17:</u> The SHs should ensure that all office staffs are trained on the appropriate use of product types.
<u>FINDING 6.18:</u> Extra NWS personnel rotated into the RFCs and WSFOs and worked many hours of overtime. The scheduling and rescheduling of leave or training for WSFO and RFC staff became a factor in maintaining adequate staffing levels.	<u>RECOMMENDATION 6.18:</u> During long, widespread record events of this type, essential personnel should return to their duty stations from long-term training assignments. Anyone withdrawn from long-term training under these conditions should be rescheduled for a later date.
<u>FINDING 6.19:</u> There are three different RFCs that provide forecasts to the St. Louis COE covering the upper Mississippi River basin (NCRFC), the Missouri River basin (MBRFC), and the lower Mississippi River basin (LMRFC). The St. Louis COE District Office expressed concern that the forecasts from the three NWS offices were not always internally consistent.	<u>RECOMMENDATION 6.19:</u> The COE and NWS should establish a technical working group consisting of personnel from all appropriate NWS and COE offices to ensure that techniques and procedures are fully understood and that clear points of contact are established to clarify any potential misunderstandings during flood events. Moreover, the NWS and COE offices should implement a personnel exchange program whereby personnel from the two agencies would work on-site in the other cooperating agency's office either part-time or full-time.

6.9 CASE STUDIES

The flooding on the Missouri and Mississippi Rivers was comprised of hundreds of smaller scale floods. These hundreds of events, which occurred in the spring and summer of 1993, are now collectively referred to as The Great Flood of 1993. It would be valuable, if time and resources permitted, to analyze in great detail most, if not all, of these events. Comprehensive analyses of all events was not possible within the scope of this report, but two cases were studied in some detail. These two cases were selected due to the hydrometeorological complexity of the events. They were also selected due to the high media visibility of the two locations during The Great Flood of 1993. The first case, the July 1993 flooding in Des Moines, Iowa, describes flooding on a relatively small basin. The second case, a very large-scale event, describes the flooding at St. Louis, Missouri, in July and August 1993. These two cases help describe the problems that can occur and the complexities that can be encountered during major floods.

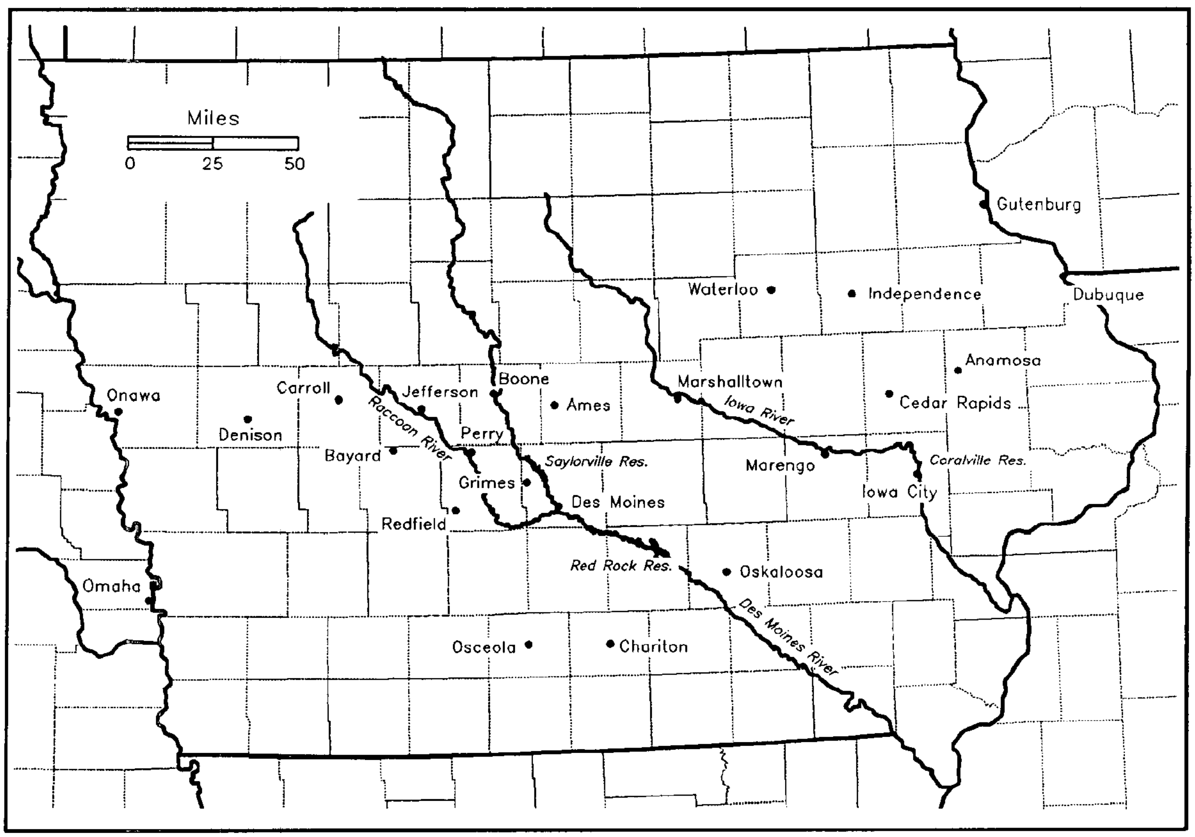


Figure 6-15. *Map of Iowa with key locations and rivers.*

6.9.1 CASE 1: DES MOINES, IOWA, FLOODING OF JULY 9-11, 1993

The following is a description of the July 1993 flooding in Des Moines, Iowa, and the events leading up to the flooding. For reference, key locations in Iowa are shown in Figure 6-15.

> "When the Fourth of July weekend rolled around, Iowa had already endured 8 consecutive months of above-normal rainfall and less-than-normal sunshine and 15 consecutive months of major flooding. Measurable rain had fallen somewhere in Iowa on 73 of the 85 days since April 10. Hundreds of thousands of acres of corn had been left unplanted. Left unplanted was 8 percent of the state's intended soybean crop--the slowest planting pace since such records have been kept. The mighty Mississippi River was flowing through downtown Davenport on its way to a record flood crest. When it seemed that nothing could get worse...things got much worse.
>
> "The largest rain event of an already extremely wet year began to take form over southwestern Iowa in the early morning hours of July 4. When the raindrops stopped falling over eastern Iowa on the afternoon of July 5, a total of 4-8 inches of rain fell across a 250-mile path from Taylor County in southwest Iowa, northeastward through Osceola, Chariton, Oskaloosa, Marengo, Cedar Rapids, Anamosa, and Dubuque. Major flooding ensued across much of southeastern Iowa, with the greatest damage reported along Clear Creek in Johnson County. The rains also pushed Coralville and Red Rock Reservoirs to record-high levels.
>
> "Unbelievably, the worst was yet to come. Strong thunderstorms moved into west-central Iowa before sunrise on July 8 and rapidly traversed eastward across the state and into Illinois by noon. A second set of stronger thunderstorms developed over west-central Iowa later in the afternoon of the 8th and slowly moved along the same path as the morning storms. By the time these storms weakened, around sunrise on July 9, a wide area of 3-9 inches of rain fell in an uninterrupted 275-mile long band from the Nebraska border at Onawa, Iowa, eastward through Denison, Carroll, Boone, Ames, Marshalltown, Waterloo, Independence, and Guttenburg.
>
> "Catastrophic flooding occurred along and south (downstream) of the rain area. Squaw Creek, in Ames, raced to record heights which flooded Iowa State University's Hilton Coliseum with 14 feet of water. Runoff into the Des Moines River sent Saylorville Reservoir to a new, record-high level for the third time in 3 weeks. The heaviest rains were concentrated in the Raccoon River basin which also sent the river to record heights. The bloated Raccoon forced thousands of West Des Moines residents from their homes and put parts of the historic Valley Junction business district under more than 5 feet of water. Farther downstream, the river flooded the Des Moines Water Works, an installation protected by dikes built 6 feet higher than the highest flood previously known.

Water service was cut off to more than one-quarter million Des Moines area residents. The Raccoon River floodwaters combined with a record crest on the Des Moines River to flood numerous electrical power substations, knocking out power to much of the Des Moines area, including all of downtown Des Moines."

Many of the tributaries feeding the Des Moines River, including the Raccoon River above Des Moines, Iowa, were slightly above flood stage during the week of July 4, 1993, although they were falling. Moderate rain (0.2-1.2 inches) fell during the 24-hour period ending 7 a.m., July 8. This slowed the falling stages of larger rivers and caused within-bank rises for some of the smaller tributaries. Then, very heavy rain (up to 7.83 inches, with several unofficial reports of more than 12 inches) occurred over the Raccoon basin and lower Des Moines River. Less widespread, moderate-to-heavy rain (1.09-3.39 inches) was reported for the period ending at 7 a.m., July 10. As most of the precipitation reports are 24-hour total cooperative observer reports, exact timing of the rainfall is uncertain. It appears, however, that most of the serious, flood-producing rainfall occurred between 7 a.m., July 8, and 7 a.m., July 9. The rainfall ending on the morning of the July 10 added to already high forecast crests.

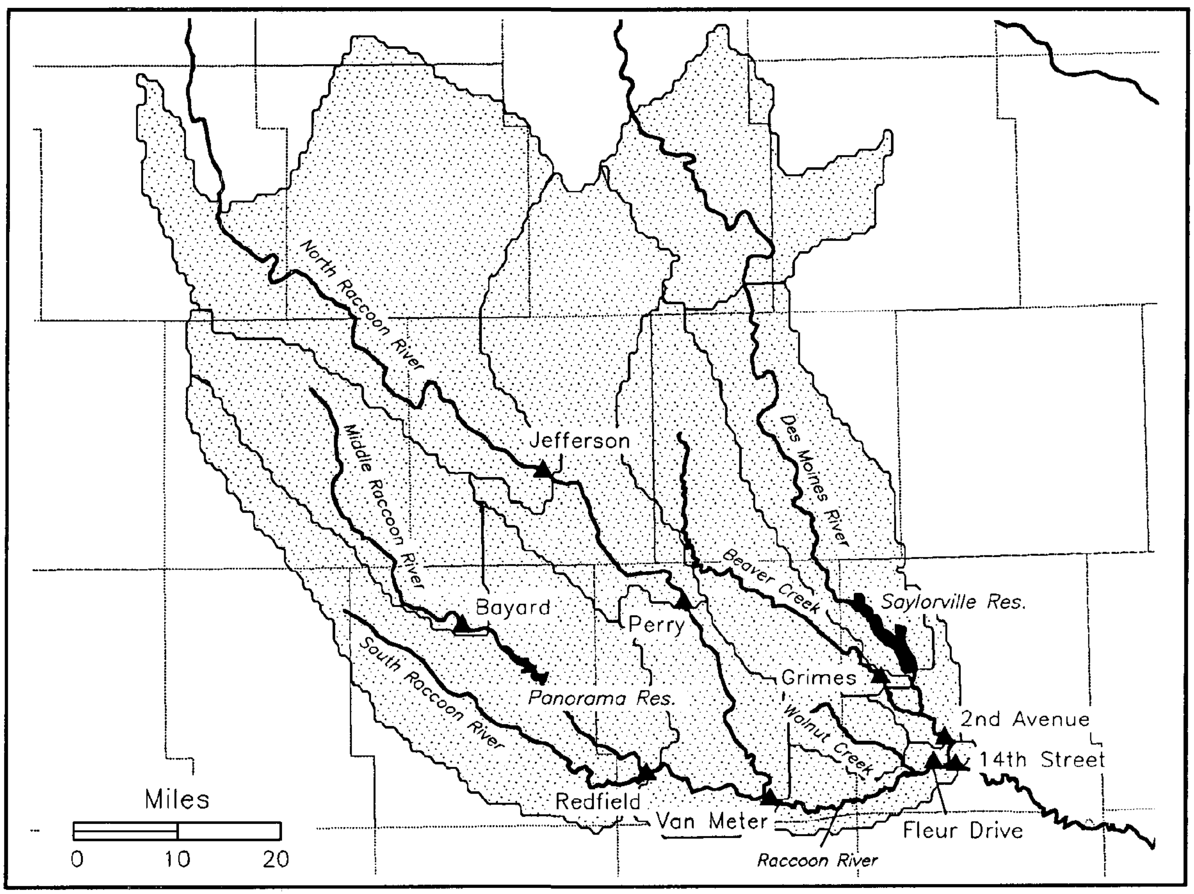


Figure 6-16. *Basin boundaries, streams, rivers, reservoirs, and NWS forecast points above Des Moines, Iowa.*

In the discussion that follows, reference to Figure 6-16, showing basin boundaries and locations of rivers and forecast points will prove useful.

The NWS issued river forecasts for three points in Des Moines, Iowa: on the Des Moines River at 2nd Avenue and SE 14th Street and on the Raccoon River at Fleur Drive. Table 6-2 summarizes the forecasts issued. Included is the approximate rainfall for the Des Moines area during the July 7-11 period.

Problems were encountered distributing the rainfall for this event. Rainfall distribution problems are typical and are frequently encountered when 24-hour total rainfall amounts, from a relatively small number of rain gages, are used to estimate rainfall distribution in both space and time for a series of complex, rapidly moving storms.

In the reach of the North Raccoon above Jefferson, Iowa, the computed[4] runoff and the resultant forecast discharges for this area (Figure 6-17) were too high. This was, most likely, due to the inability to accurately resolve details of the rainfall distribution. Because model procedures route water volumes from upstream locations to points further down the river, this error in both magnitude and timing in the upper reaches of the Raccoon River had the additional effect of causing the crest to be forecast late for Fleur Drive and at Van Meter, Iowa.

Problems determining the timing of the rainfall are obvious at Beaver Creek at Grimes, Iowa, (Figure 6-18) 15 miles north of Des Moines. (Although Beaver Creek at Grimes is a data point and not a forecast point, it is used in this case study.) At Grimes, peak discharge exceeding the previous record was successfully predicted; however, the forecast peak was 42 hours late. Based on the Beaver Creek response to the rainfall, it is possible to determine that additional rain (rain not accounted for by the sparse rainfall network) fell in the southern reaches of the basin. This appears to have caused a more rapid rise on Beaver Creek than would have occurred if the rainfall had been evenly distributed over the basin, as is usually assumed with current lumped parameter modeling procedures. This analysis is possible after the fact, with the aid of observed river stages. Analysis of the rainfall reports, available to the forecaster at the time of the forecast, does not indicate problems with the rainfall distribution analysis. The problem stems from forecasting with too few rainfall reports to define precisely the rainfall distribution that occurred. This problem also appeared at forecast points in the Raccoon basin during this event.

---

[4] A major focus of this case study is the runoff and streamflow computations of the NCRFC modeling systems and the impact of these computed values on RFC forecasts. Figures 6-17 through 6-23 show "computed" hydrographs (and in some cases "routed" hydrographs) that are composites of model computations based, in all cases, on observed rainfall data. For example, every computed value shown with an "x" on Figure 6-17 is computed based on observed rainfall prior to the "x," processed through the NCRFC hydrologic analysis and modeling procedures. These computed values are also derived in "open-loop" fashion, i.e., model values are not adjusted to track observed stream conditions. This approach to the case study was adopted to simplify the exposition while preserving a focus on key issues. It does not capture, however, many of the forecasting complexities created by uncertainties in future precipitation or the forecast update cycle.

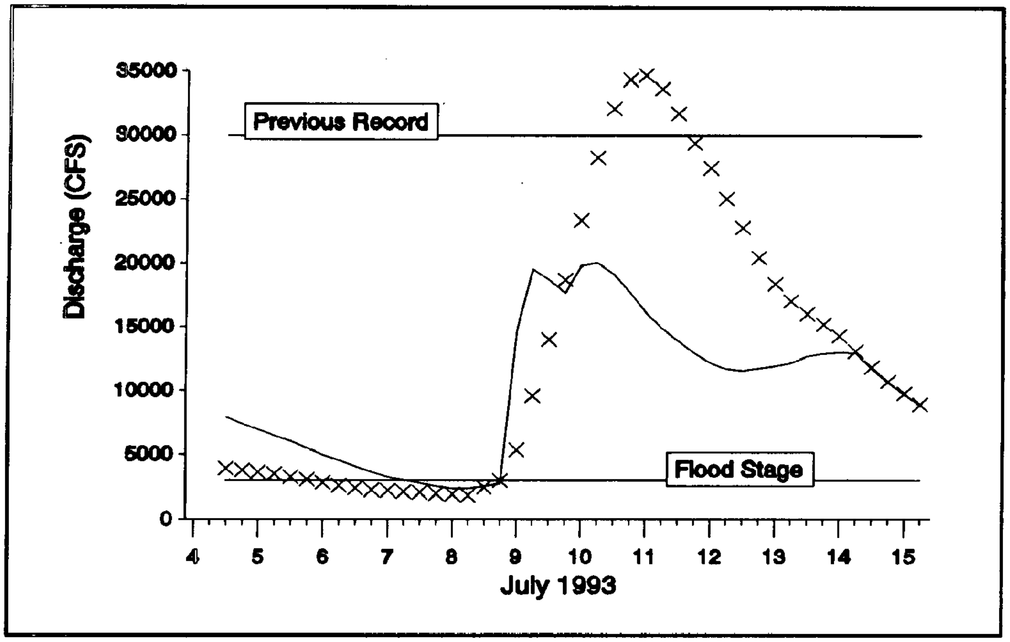


Figure 6-17. *North Raccoon River at Jefferson, Iowa, observed (solid line) and computed (x) discharges, July 4-15, 1993.*

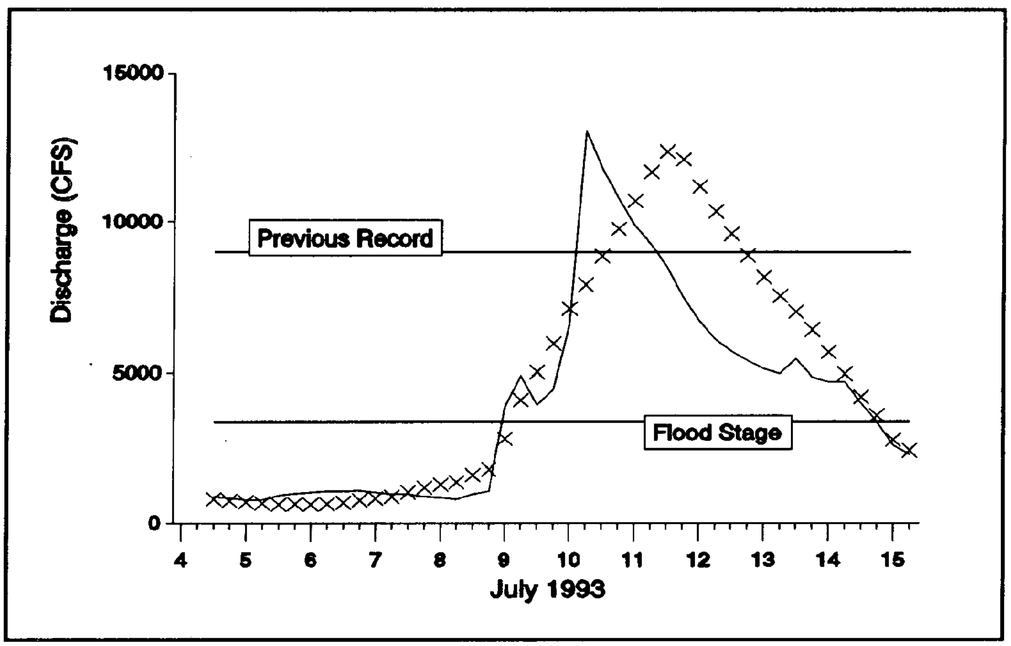


Figure 6-18. *Beaver Creek at Grimes, Iowa, observed (solid line) and computed (x) discharges, July 4-15, 1993.*

Table 6-2. *Summary of crest forecasts for Des Moines, including precipitation observations.*

DES MOINES RIVER

	Old Record		7/9 Friday			7/10 Saturday Midday		
	Stage	Year	Stage	Forecast	Date	Stage	Forecast	Date
2nd Ave.	30.2	1954	24.2	30.0	7/9	27.1	29.5 - 30	7/11
SE 14th	39.8	1965	27.94	32.0	7/11	30.6	33.0 - 34	7/11

	7/10 Saturday Night			7/11 Sunday	
	Stage	Forecast	Date	Stage	Forecast
2nd Ave.	29.0	29.5 - 30	7/11	31.5	Crested 31.6
SE 14th	32.2	33.5 - 34	7/11	34.0	Near Crest Now

RACCOON RIVER

	Old Record		7/9 Friday			7/10 Saturday Midday		
	Stage	Year	Stage	Forecast	Date	Stage	Forecast	Date
Fleur Dr.	19.8	1947	15.9	21.0	7/13	18.5	22.0	7/12

	7/10 Saturday Night			7/11 Sunday	
	Stage	Forecast	Date	Stage	Forecast
Fleur Dr.	22.6	24 - 25	7/11	26.0	Near Crest

RAINFALL

7/8 - 7/9 Thur. & Fri. (AM)	7/9 - 7/10 Fri. & Sat. (AM)	7/10 - 7/11 Sat. & Sun. (AM)
3 - 7.8 in.	0.25 in.	0.5 - 3.0 in. (4.5 at Slater)

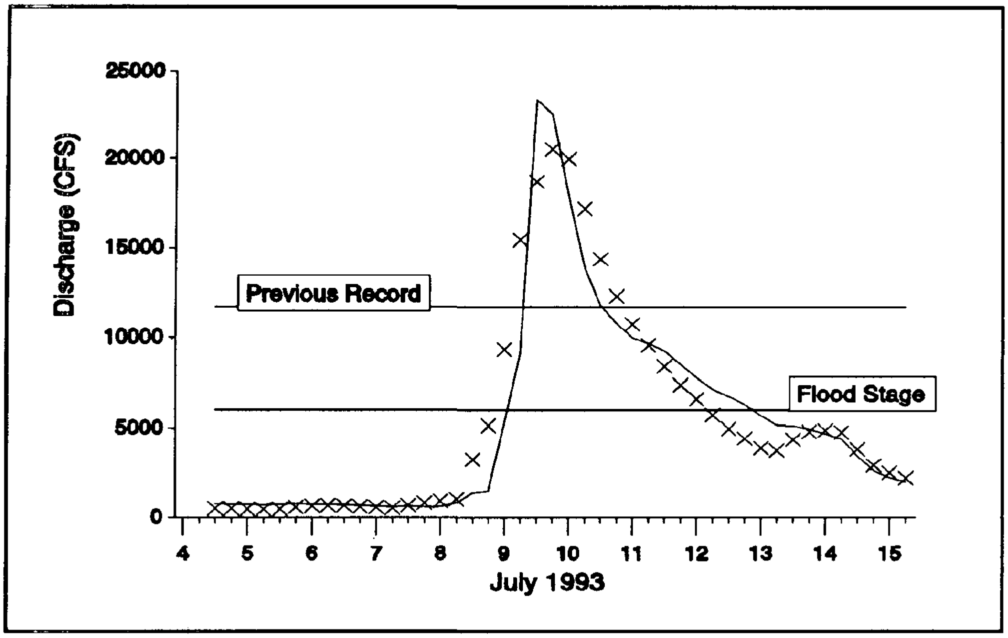


Figure 6-19. *Middle Raccoon River at Bayard, Iowa, observed (solid line) and computed (x) discharges, July 4-15, 1993.*

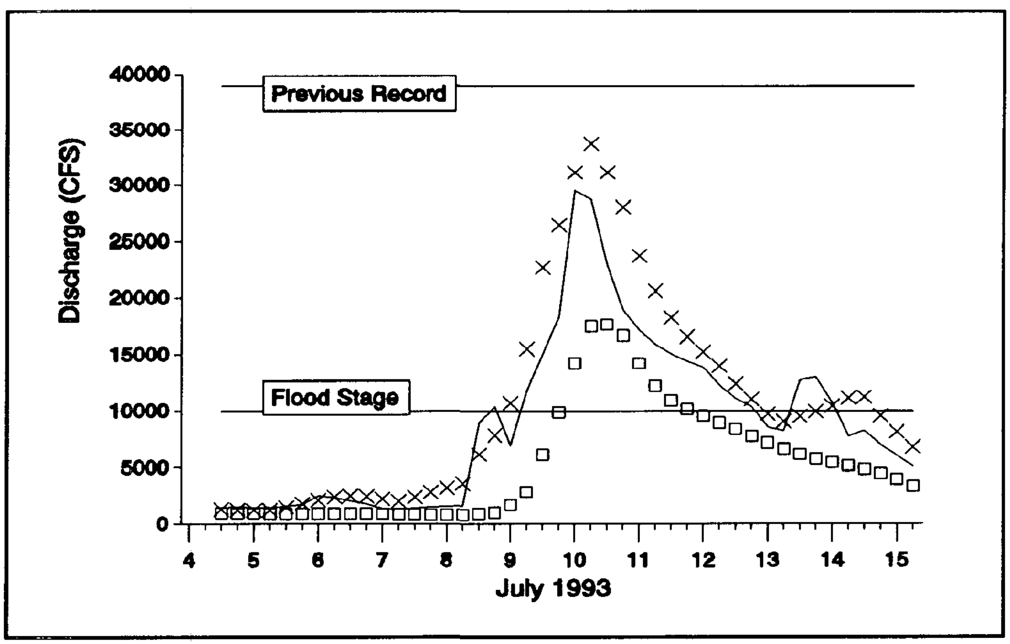


Figure 6-20. *South Raccoon River at Redfield, Iowa, observed (solid line), computed (x), and routed (open box) discharge, July 4-15, 1993.*

About 50 percent of the runoff at Van Meter came from the Middle Raccoon River at Bayard, Iowa, and the South Raccoon River at Redfield, Iowa. This reach of the river was successfully modeled and forecast by the NCRFC (Figures 6-19 and 6-20) rather well. The peak discharges at both points far exceeded flood flow levels. As shown in Figure 6-19, the peak discharge at Bayard was double the previous record. The remaining runoff at Van Meter came from the North Raccoon River above Perry, Iowa, and from contributions to the reach between Perry, Iowa, and the confluence of the North Raccoon River with the Middle Raccoon River at Van Meter, Iowa. Forecasting runoff from this reach of the Raccoon River proved particularly challenging for this event due to a variety of circumstances. The volume of water predicted from this reach of the river by RFC hydrologic modeling was reasonably accurate. The distribution of the rain was placed too far north and consequently resulted in a forecast timing problem. The main problems, however, appear to have been: (1) the absence of an established stage discharge relation and (2) insufficient river gage readings from the gage at Perry, Iowa, available to the RFC. As a result, the RFC forecaster had insufficient information and consequently routed too little water downstream. This undercomputation of streamflow volume went undetected until the crest reached Van Meter. Had the volume problem been detected earlier, more forecast lead-time could possibly have been provided at Van Meter and Fleur Drive.

The gage on the North Raccoon River at Perry, Iowa, also proved to be a challenge for the RFC forecaster for two reasons. First, the gage is not rated; the stage-discharge relation is based only on empirical evidence. It is not based on discharge measurements taken over time and under various circumstances. Also, the crest at Perry exceeded the maximum stage of record. Discharges inferred from the reported stages were, therefore, subject to large errors. Second, in spite of the fact that flows at Perry had been running at near-flood stage for some time, stages were received by the RFC only once every 24 hours on the rising limb of the flood crest. Five additional stage readings, however, were made at Perry on July 9 that were never available to the RFC.

Since the discharge inferred from the observed stage at Perry was "believed" by the forecaster (in contrast to the discharge computed by RFC models), that volume of water estimated from the observed stage was routed downstream to Van Meter. Figure 6-21 shows a difference of as much as 14,000 cfs between the computed and observed discharge (according to the presumably inaccurate rating) on the North Raccoon River at Perry. Figure 6-22 shows the observed, computed, and routed flows on the Raccoon River at Van Meter. The routed flows at Van Meter are based on the observed flows at Redfield (see Figure 6-20) plus the observed flows at Perry. If 14,000 cfs is added to the computed flows at Perry and routed to Van Meter, the recomputed hydrograph at Van Meter is depicted in Figure 6-23. It also clearly shows that distributing the rainfall too far upstream in the basin resulted in a late, flat forecast crest at Van Meter.

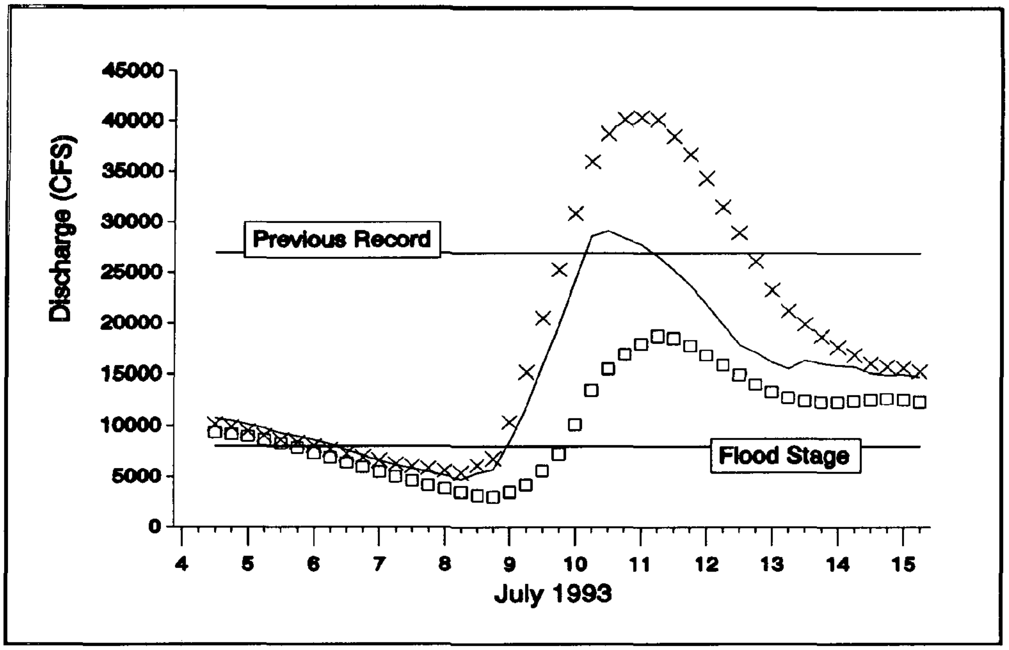


Figure 6-21. *North Raccoon River at Perry, Iowa, observed (solid line), computed (x), and routed (open box) discharges, July 4-15, 1993.*

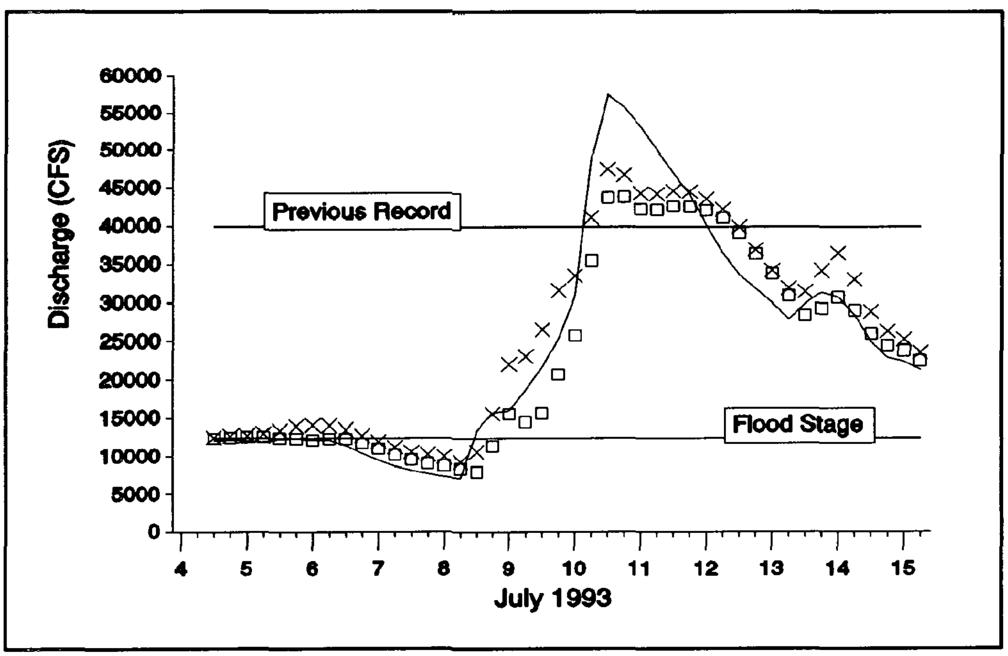


Figure 6-22. *Raccoon River at Van Meter, Iowa, observed (solid line), computed (x), and routed (open box) discharges, July 4-15, 1993.*

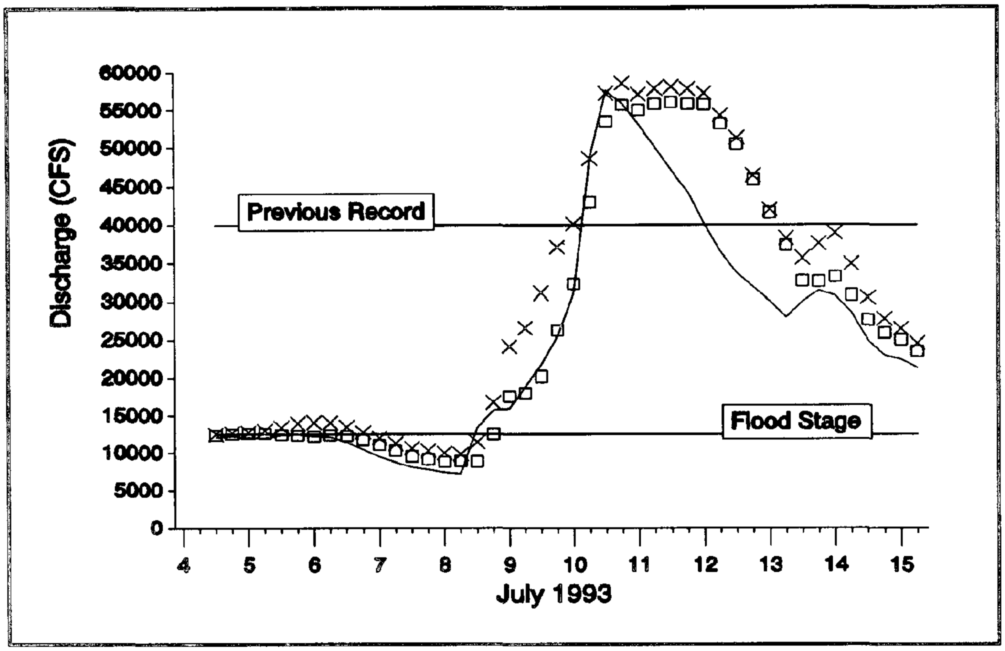


Figure 6-23. *Recomputed forecast at Van Meter, Iowa, observed (solid line), computed (x), and recomputed routed (open box), July 4-15, 1993.*

Two additional factors probably contributed to the forecast discharge at Van Meter being lower and later than observed: (1) the flow from Perry to Van Meter probably traveled faster than computed by RFC models, and (2) the rainfall in the local area between Perry and Van Meter, most likely, was greater than indicated by analyses available to the RFC.

The observed volume of water at Van Meter was much larger than had previously been observed. The flood wave traveled faster than expected and arrived earlier than forecast at Van Meter. The crest at Van Meter exceeded the maximum flow of record, and the flood crest traveled between Van Meter and Fleur Drive in Des Moines much faster than had been previously observed. This resulted in a crest that was higher and arrived earlier than forecast at both Van Meter and Fleur Drive in Des Moines.

Some Des Moines residents felt that releases from Panorama Reservoir on the Middle Raccoon River may have contributed to the problems in forecasting Van Meter. Evidence does not support this assumption. Panorama Reservoir is upstream of the Redfield, Iowa, gage. No problems were encountered with the Redfield forecast (see Figure 6-20).

It has been suggested that backwater from the Des Moines River at Des Moines contributed to the flooding along the Raccoon River in Des Moines. Backwater from the Des Moines River has been known for many years to be a problem at lower flows along this reach. Previous backwater studies and recent field work by NCRFC hydrologists, however, support the view by the COE that backwater had very little, if any, effect on the elevation of the crest on the Raccoon River at Des Moines during the flooding on July 11, 1993.

The telephone line for the Limited Automatic Remote Collector (LARC) River gage at Van Meter went down between 4:30 and 5 a.m. on July 10. It was back on-line about 10 p.m., July 11. On July 10 at about 4:30 a.m., the LARC was reading 22.28 feet and was rising. When the phone line was repaired on July 11 at about 10 p.m., the reading was 23.20 feet and was falling. The data collection platform (DCP) at the same site also became unreliable due to an orifice problem that occurred after the crest. The orifice line was ripped loose early Sunday morning, July 11 (between 1:30 and 1:45 a.m.). This occurred after the crest (25.83 feet at 2 p.m. CDT, July 10). The DCP gage was repaired by 11 a.m., Sunday morning, July 11. The absence of the LARC data, which was being automatically fed to the hydrologic modeling system, caused delays both at the RFC and the Des Moines WSFO. Since the river was rising faster than anyone had ever observed, the forecasters were suspicious of the DCP readings. It was assumed that a problem had occurred with the gage itself. It was not until several hours later that a manual observation at Van Meter confirmed the validity of the DCP reading. Nonetheless, hours had been lost in updating the Van Meter and Fleur Drive forecasts at a very crucial time.

The following general observations can be made about this event:

1. An inability to determine the amount and time distribution of rain led to errors in forecasts for both the volume and the timing of flood crests. The analysis of the precipitation field was hampered by insufficient rainfall observations.

2. Lack of an established stage-discharge relation (i.e., rating curve) at a key point (North Raccoon River near Perry, Iowa) made interpretation of the stage data (the conversion to streamflow) subject to error. Therefore, the computed flows for routing downstream were also subject to error.

3. At Perry, Iowa, a key point upstream from Van Meter and Des Moines, 24 hours elapsed between readings of 15.85 feet at 7 a.m., July 9, and a reading of 22.90 feet at 7 a.m., July 10, that were available to the RFC. Five additional stage readings, however, were made at Perry on July 9 that were never available to the RFC. This occurred in spite of the fact that the 15.85 feet reading exceeded flood stage by almost 3 feet. The reading 24 hours later exceeded the previous flood of record by 0.2 foot.

4. Information from other key river gages was disrupted when they were most needed (near the crest) due to telephone line outages.

5. Many of the river stages exceeded their historic records. Out of necessity, the rating curves for these streams were extended by the hydrologists at the RFC. Some of these rating curve extensions may not have reflected the true flow, resulting in inaccurate forecasts downstream. This is almost certainly true for the unrated gage at Perry.

6. Lack of on-site computer capability at the NCRFC was a factor. This limitation would have been even worse if RFC staff had not been innovative in exploiting the office's local PC system to augment the central-site computational capability.

7. Current hardware and software technology at RFCs and WSFOs inhibited forecasters from retrieving and managing operational data in a timely manner. Forecasters at the RFCs and WSFOs were repeatedly forced to manually analyze and interpret observational data. This resulted in confusion about the data and delays in releasing forecasts.

8. Historically, the vast majority of the data needed to drive RFC forecast models is collected or transmitted every 6 hours on synoptic times. At night, when human observers were sleeping, little, if any, data were available. Over time, operational procedures have evolved based on these data availability constraints. Today, with automation, more observational data are becoming available around the clock, but operational procedures have not kept up with the pace of this automation. Automated data available during this event could have supported more frequent forecast updates, but limitations in data analysis and modeling systems, the comparatively inefficient batch-processing computer environment, and the sheer magnitude of the event generally required forecasters to wait for more complete data that were available at synoptic times.

9. Lack of integrated, objective techniques to use QPF and satellite precipitation estimates was a problem during this event. With the technology currently available, the RFC staff made excellent use of both QPF and satellite precipitation estimates. Neither of these products can be used directly in hydrologic models without significant analysis and reprocessing (see Appendix B). Since interactive, graphics-based analysis methods are not yet available at the RFC, both products are currently being used only subjectively, which seriously limits their utility.

10. Not enough information is contained in crest forecasts. Meteorological offices and the public did not understand the science behind the adjustment of the crest and the changes in the timing of the crest based on the occurrence of additional rain. For specialized users, such as the COE, this problem would be mitigated by sending total hydrographs as forecasts.

11. Because the current implementation of RFC models makes calculations at only 6-hour intervals, forecasters are prevented from effectively integrating data that are observed at "intermediate" times during flood situations.

12. River flow travel times were overestimated at the record flows experienced in this storm.

FINDING 6.20: An inability to determine accurately the amount and time distribution of precipitation led to uncertainty in forecasting both volume and timing of flood crests. As specifically noted in the Des Moines, Iowa, case study, inaccurate precipitation estimates are generally considered to be the greatest single source of river forecast error. The NWS plans to produce precipitation estimates which combine rain gage observations, WSR-88D precipitation estimates, and satellite observations in sophisticated, multistage, multisensor precipitation estimates using both interactive and automated quality-control features. These plans require the completion of the WSR-88D radar net-work and the on-site, interactive processing provided by AWIPS.	**RECOMMENDATION 6.20:** Completion of the WSR-88D network and the AWIPS program must continue to have high priority (see also Recommendations 5.14 and 5.15).
FINDING 6.21: Record flows occurred earlier than were forecast at many points along the Des Moines River and its tributaries due, in part, to routing procedures that overestimated travel times. Current routing procedures are based on observed hydrograph data from previous floods.	**RECOMMENDATION 6.21:** Empirical routing procedures should be recalibrated to account for maximum discharges that occurred during The Great Flood of 1993.

6.9.2 CASE 2: MISSISSIPPI RIVER FLOOD AT ST. LOUIS

This case study examines the problems encountered by the staffs of the NCRFC and the MBRFC, as well as the WSFO at St. Louis, Missouri, as they collaborated to forecast the Mississippi River at St. Louis. As flood-producing rainfall pummeled the Midwest during the summer of 1993, the staffs of these three NWS offices battled to update the flood forecasts along the Missouri and Mississippi Rivers during an ever-changing scenario. This effort culminated in the forecasts at St. Louis, Missouri, on the Mississippi River just below the confluence with the Missouri River. The combination of these two river basins comprise more than one-fourth of the area of the continental United States. All of the precipitation falling on this part of the United States must be accounted for in the river forecasts at St. Louis, since all of the surface drainage flowing out of this quarter of the Nation flows past St. Louis.

The NWS has been criticized for the quality of forecasts on the Mississippi River at St. Louis, Missouri. Much of this criticism is based on a belief that the NWS did not use current stage-discharge relations and ignored or misused the discharge measurements provided by the U.S. Geological Survey (USGS) and the COE during this event. The main focus of this case study, therefore, is on the use of rating curves and discharge measurements by the NWS RFCs responsible for forecasting this flood.

The NCRFC, in Minneapolis, Minnesota, is responsible for forecasting the Mississippi River basin above St. Louis except for the Missouri River basin, which is the responsibility of the MBRFC at Kansas City, Missouri. The St. Louis WSFO is responsible for producing flood watches and warnings based on RFC guidance and disseminating these products to the public for the areas indicated in Section 6.3. WSFO St. Louis was the focus of much of the flood forecasting in the Midwest during the summer of 1993 as numerous locations on both the Missouri and Mississippi Rivers recorded record crests time and again.

The following description of the 1993 flooding on the Mississippi and Missouri Rivers was written by Jack Burns, SH, WSFO St. Louis:

> "June and July 1993 were months of record flooding on the Missouri and Mississippi Rivers. In the area served by the St. Louis WSFO, a total of 41 forecast points in the state of Missouri were above flood stage at some time during the month of June. In July, 59 locations in Missouri were above flood stage.
>
> "For the state of Missouri, a total of 34 locations set river stage records: 12 on the Mississippi River, 12 on the Missouri River, 5 on the Grand River in north-central Missouri, 2 on the Platte River in northwestern Missouri, and the remainder on the Lamine, the Marmaton, and the Moreau Rivers in west and central Missouri. The end of August marked 153 consecutive days that the

Mississippi River at Hannibal, Louisiana[5], and Clarksville remained above their respective flood stages.

"This flood broke river stage records established on the Mississippi River in April 1973 and on the Missouri River in July 1951. Serious flooding below the confluence of the Ohio River was spared due to the low-flow levels on the Ohio River aided with the use of flood control storage at the Barkley and Kentucky Reservoirs [on the Cumberland and Tennessee Rivers which are major tributaries to the lower Ohio River].

"In April, the Mississippi River had crested 6-10 feet above flood stage and, once again, near the same stage levels during May. At the beginning of June, the river had dropped below flood stage and was still falling. During the second week of June, the river level rose 5 feet to near flood stage and again began a very slow recession. The Mississippi River, 2 weeks later, was 4 feet below flood stage at St. Louis but still near flood stage at other locations from Quincy to Cape Girardeau, Illinois.

"The month of July brought more heavy rains north of Missouri in the upper Mississippi and Missouri River states of Iowa, Kansas, Nebraska, North and South Dakota, and Minnesota. Rainfall amounts of 5-7 inches in 24 hours were common. Hamburg, Iowa, reported nearly 10 inches of rain in 48 hours.

"Rains continued during the month of July and resulted in record-setting crests moving down the Mississippi and Missouri Rivers. Both record crests reached the confluence of the Mississippi and Missouri Rivers within days of one another.

"The Mississippi River stage paused for a few days at the April 1973 record stages, seemingly waiting for the Missouri River water to arrive and then began driving upward again--breaking levees, chasing people with their portable property to higher ground, and generally causing havoc and mayhem with anything in its path--to new record river stage levels.

"The crest, now combined as one, moved downstream through St. Louis and Chester, Illinois, on a course to the southern tip of Illinois at Cairo. With the Ohio River at low water levels, the Mississippi River flood crest joined with the Ohio River flows and continued downstream toward Memphis but now at less than bankfull levels. As the flood crest moved past Cairo, the COE curtailed outflows from the Barkley and Kentucky Reservoirs to allow the crest to pass.

---

[5] Note that in this case Louisiana is a <u>city</u> in Missouri along the Mississippi River and not the state in which Hannibal is located.

"Beginning as early as June 7, reports of levee breaches and then levee breaks became common on the Mississippi and Missouri Rivers. The effect on the forecast was to delay the crests, but the water kept coming. Automatic gages malfunctioned and backup observers, in many cases the COE, were called on for river stage measurements. The USGS made daily, and sometimes more frequent, flow measurements of the rising water up and down the rivers.

"Major sandbagging took place on the lower Missouri River, the River Des Peres in St. Louis, the Mississippi River south of St. Louis, and many other rivers over the state of Missouri. While some efforts were successful, many were not as the river continued its rampage.

"More than 1,000 flood warnings and statements, 5 times normal, were written to contend with the rising waters to inform the public that we were dealing with the wrath of a river not seen since water stage records have been kept at St. Louis. The 52-foot St. Louis flood wall, built to handle the volume of the 1844 flood, was able to keep this flood out of the city with just more than 2 feet to spare.

"On August 1, a levee broke near Columbia, Illinois, to eventually flood 47,000 acres of land and inundate the towns of Valmeyer and Fults, Illinois. The freed flood waters continued to flow to the south, parallel to the river, approaching levees providing protection to the historic areas of Prairie du Rocher and Fort de Chartres, Illinois. On August 3, the COE, using a drag shovel and eventually dynamite, made several breaks through the Mississippi River levee to provide a passage for the flood waters to flow back into the river. The innovative plan worked, and the historic areas were saved from the flood waters.

"On the Missouri River, the COE has estimated that nearly all of the 700 privately built agricultural levees had been overtopped or destroyed. In late June 1993, high water levels caused many locks on the upper Mississippi River to close, shutting down navigation and impeding commerce. In early July, as the rainfall continued, more than 600 miles of the upper Mississippi River, 500 miles of the Missouri River, and 60 miles of the Illinois River had to be closed to vessel traffic. River levels remained high through all of July and much of August. The levels finally dropped enough by August 27 that all the locks in the system were opened for the first time since June."

Analysis:

To produce the forecast for the Mississippi River at St. Louis, flows for the Missouri River above Hermann, Missouri, must be used. The MBRFC in Kansas City forecasts the Missouri River at Hermann. The flows computed by the MBRFC are transferred electronically to the

NCRFC modeling system where they are combined with the flows from the upper Mississippi River to produce the forecasts for St. Louis. MBRFC forecasts for the Missouri River at Hermann, Missouri, are described in Section 6.5.2 and shown in Appendix F. NCRFC forecasts for the Mississippi River at St. Louis are described in Section 6.4.2 and shown in Figures 6-6 and 6-7 and in Appendix F.

The NCRFC and MBRFC use computer models to simulate the streamflow over the entire Missouri and Mississippi basins above St. Louis. The information available to these models is updated as rainfall reports are received. Computed streamflow is modified based on measured streamflow provided by various observers. The most frequently available information is the stage (water level). Observations of river flows (discharge measurements) are much more difficult to collect but are essential to develop rating curves that reflect true stage-discharge relations. RFC hydrologic models compute streamflow that is then converted to stages to produce forecasts of stages. Rating curves are also used to convert observations of stages into flow rates. A major challenge when forecasting rivers like the Missouri and Mississippi comes from problems of converting observations of stage to flow. A brief discussion of rating curves and how they are used by river forecasters follows.

A rating curve is developed by making measurements over a period of time to define a relation between streamflow rate, or discharge, and the gage height, or stage, at the gaging site. Rating curves are checked periodically to ensure that the relation between the discharge and gage height has remained constant. Scouring of the stream bed or deposition of sediment (fill) in the stream can cause the rating curve to change so that the same discharge produces a different recorded gage height, or stage.

"Official" rating curves are adjusted based on streamflow measurements made by the USGS, COE, and others. Adjustments to the official rating are made after detailed analysis by the office responsible for determining the official streamflow record at a given site. These official rating adjustments are not available in real-time because time is required to perform the detailed analysis of the rating.

Current discharge measurements are made available to the RFCs to allow the RFC forecaster to compensate for rating shifts. Discharge measurements, due to the manner in which they must be made, are subject to considerable error. Therefore, official discharge measurements are made available only after detailed analysis is completed by the office responsible for the discharge measurement. Out of necessity, river forecasters analyze and adjust rating curves used in river forecasting in real-time. These adjustments by the river forecaster are based on: (1) provisional discharge measurements provided by the offices making the discharge measurements and (2) experience and analysis of the feedback provided by the response of the RFC hydrologic models.

This dynamic rating analysis is especially important in forecasting streams, such as the Missouri and Mississippi Rivers, where scour and fill provide some of the major challenges to the forecaster. Also, in rivers with gentle slopes, discharge for a given stage when the river is rising may exceed discharge for the same stage when the river is falling. This dynamic effect can be a factor in the Missouri River and the Mississippi River near St. Louis; adjustment factors must be considered in calculating discharge for rising and falling stages. At any time, professional judgment of the true rating at a point can and does vary. These differences of opinion about the official rating arise primarily from the ratings being used for different purposes. At NCRFC, no single hydrologist is solely responsible for determining a valid rating. A team effort is employed to review a rating based on the latest available information and experience from the hydrologist staff. Senior staff members are involved in this process.

It is important to understand the rating analysis performed by both RFCs necessary to produce a successful forecast for St. Louis. Figure 6-24 shows the stage discharge relation for the Mississippi River at St. Louis. The rating curve is shown as a solid line. Recent discharge measurements made by the USGS and COE are also shown as triangles. Most of these measurements were made in July 1993. A similar rating for the Missouri River at Hermann, Missouri, is shown in Figure 6-25. The rating curve for the Mississippi River at St. Louis (Figure 6-24) shows a variability in flow of around 15 percent at about 46 feet. USGS measurements taken on successive days (July 20 and 21) show a difference of discharge of 12 percent with no change of stage. Similar variability is shown in Figure 6-25 for the rating for the Missouri River at Hermann. This variance required additional analysis to provide the best forecast possible.

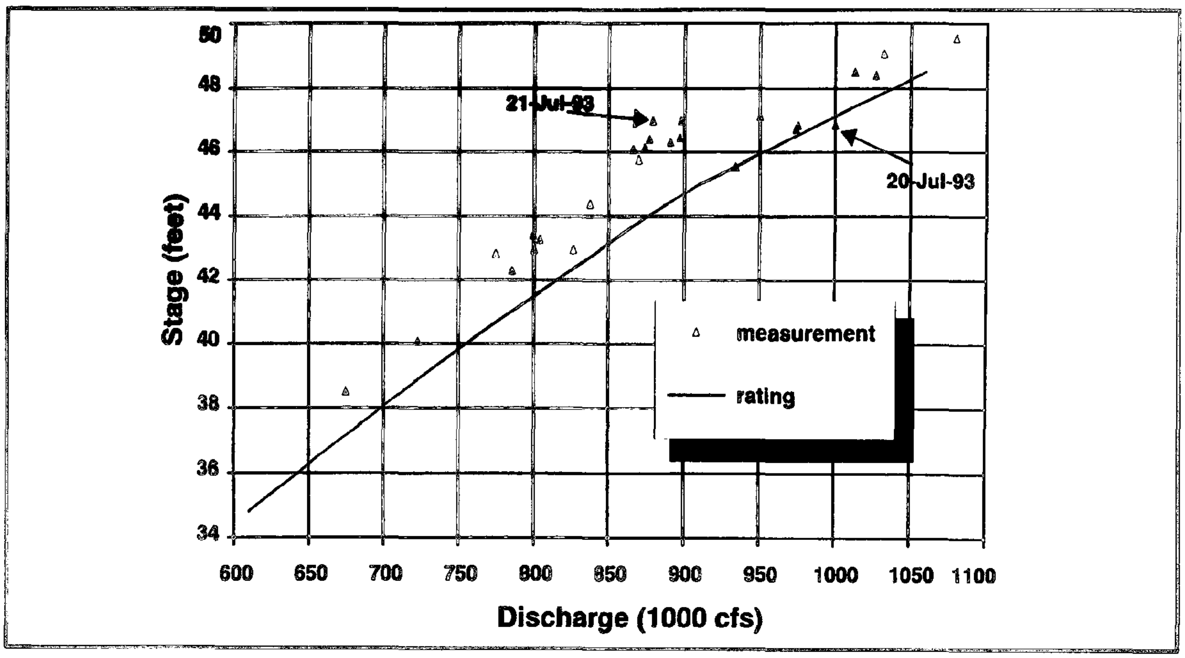


Figure 6-24. *Rating curve on the Mississippi River at St. Louis.*

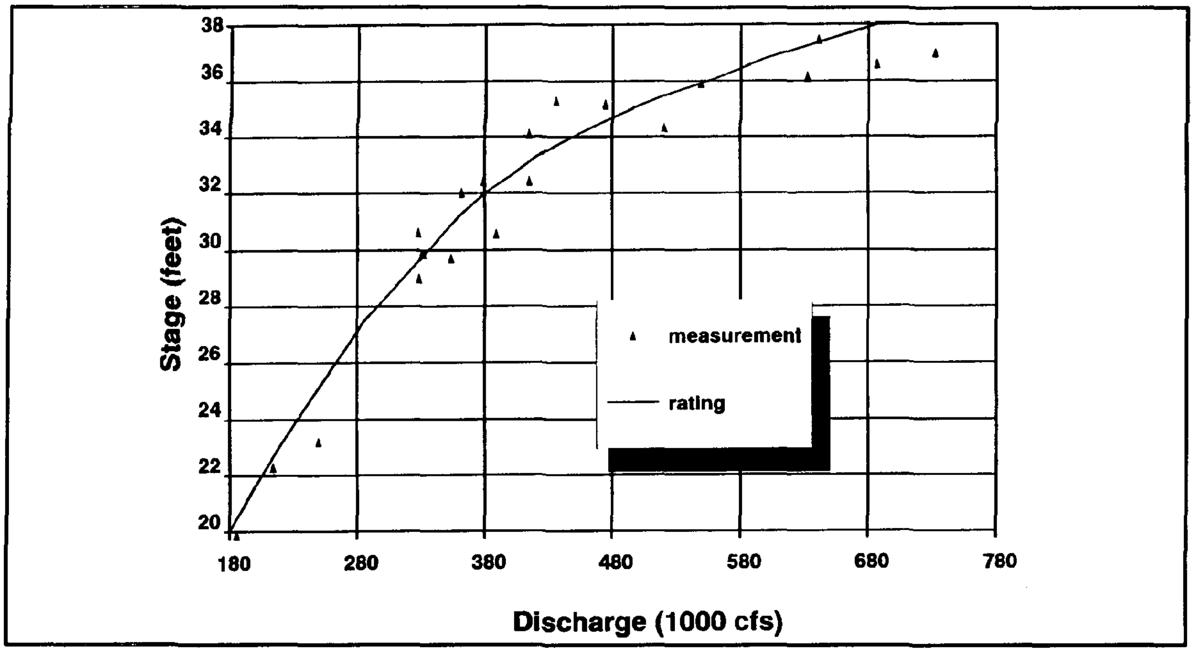


Figure 6-25. *Rating curve on the Missouri River at Hermann, Missouri.*

Not all of the analysis concerning the rating curve shifts was done in-house at the NCRFC. Additional experts were consulted. For example, on July 26, 1993, after the second record crest had passed St. Louis, and before the third record crest arrived on August 1, the NCRFC requested assistance from the NWS Office of Hydrology's Hydrologic Research Laboratory (HRL), in Silver Spring, Maryland. The NCRFC asked for a second opinion concerning its analysis of the stage-discharge relation at St. Louis for the third crest. At that time, the NCRFC was computing 1,036,000 cfs flow with a stage of 48.0 feet at the crest on August 1. After analysis, HRL concurred with the NCRFC analysis. HRL concluded that dynamic effects would be very small and would not be a factor: any shift in the rating would be due to changes in cross-sections resulting from scour and fill. After additional rain, rating shifts, and levee failures, the NCRFC revised the crest forecast up to 49.7 for August 1, 1993. The observed crest was 49.6 feet on August 1.

The following general observations can be made about this event:

1. The suggestion that NWS RFCs did not make proper use of ratings and discharge measurements is not supported by the evidence. Both MBRFC and NCRFC effectively used discharge measurements to adjust their ratings and forecasts in real-time.

2. Discharge measurements were made very frequently during this event by the USGS and COE. All of the NWS offices needing the measurements, however, did not receive all of the information on the same day. Many measurements were received in a haphazard way. Frequently, RFCs learned of the availability of a new discharge measurement during a teleconference. Also, NWS offices were not aware of the schedules for the measurements, so they were not able to ascertain that they did not have the latest rating. Better coordination and distribution of this vital information is critical to improved flood forecasting.

3. During major events, information must be exchanged in real-time among the providers and users of hydrologic information, such as the NWS, COE, USGS, and others. All users of this information should have the ability to receive the information as quickly as possible. They should also have the technology necessary to visualize the information, including discharge measurements, rating curve shifts, computed flows, forecasts, precipitation field analysis, soil moisture accounting values, river routings, etc.

4. Levee failures caused many forecasting problems. RFCs do not have good models to allow analysis of levee failures in real-time. Revision of forecasts based on levee failures was very manpower intensive and caused extra delays. Use of the best available technology and improved flood routing models, as well as Geographic Information Systems at the RFCs, would help greatly in these situations.

5. Coordination between the MBRFC and NCRFC for the Missouri River forecast at Hermann, Missouri, was critical. Attempts to coordinate over the telephone were partially successful, but technology that would allow the Hermann forecaster at MBRFC and the St. Louis forecaster at NCRFC to simultaneously visualize all of the information used in their forecasts would have been of great value.

6. The forecasters and users of the forecasts expressed the need for additional information in river forecasts required to do proper risk analysis. Forecasters compute total hydrographs for their forecast points, and they have ideas concerning the variability that may occur in the forecasts due to uncertainties such as levee failures and rating shifts. The forecasts, however, are for single-point crest forecasts at a specific time (e.g., 49.7 feet on August 1, 1993). Consideration should be given to releasing total forecast hydrographs with bracketed numbers indicating the level of uncertainty that could be expected for the crest.

CHAPTER 7

COORDINATION AND DISSEMINATION

One of the fundamental objectives of the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) is to reduce the loss of life and property resulting from meteorological and hydrological events. This is done by combining efforts and sharing resources with other agencies and by ensuring that information is disseminated through the most effective means available.

7.1 INTRA-AGENCY COORDINATION

Coordination among individual Weather Service Forecast Offices (WSFO)/Weather Service Offices (WSO), River Forecast Centers (RFC), national centers, and regional and national headquarters is a vital part of the warning process. During The Great Flood of 1993, there was frequent coordination among all components of the NWS. Special teleconferences involving the RFCs, the WSFOs, the National Meteorological Center (NMC), and the Office of Hydrology were held during the event to improve forecast coordination. During peak flooding, daily teleconferences were held in the Central Region with key NWS field offices in the Central Region and in the Southern Region. In this way, it was possible to keep all critical offices abreast of local hydrometeorological issues on a daily or more frequent basis.

The teleconferences used standard audio-telephone links, but future, significant, long-duration events might profit from video teleconferencing since visual aids could help discussions that often center on location, severity, and movement of weather systems. Video teleconferencing capabilities currently require at least a week for installation even on an emergency basis, though a few months is more typical.

Service Hydrologists at the WSFOs stayed in contact with RFC hydrologists to keep the forecasts updated. The RFCs were staffed 24 hours a day for parts of the flood event and for extended hours of operation throughout the event. Service Hydrologists mentioned that additional RFC support and coordination would have been helpful, on occasion, during the time when the RFCs were closed. Additionally, Service Hydrologists noted that the use of different RFC product transmission formats caused them to spend extra time editing RFC products before issuing them. Similarly, WSFOs and WSOs expressed varying degrees of satisfaction with RFC services. The presence or absence of a staff Service Hydrologist, collocation of the WSFO/WSO and RFC, and WSFO/WSO staffing levels were important considerations during the peak flood event.

RFC, WSFO, and WSO personnel routinely coordinated with various Federal, state, and local Emergency Operations Centers (EOC). Coordination was typically provided by frequent telephone contact and also by NWS personnel on-site at specific EOCs during critical periods.

In one instance, confusion occurred for several local governments and Emergency Management Agencies (EMA) when internal NWS discussion products were distributed and appeared to represent official NWS forecasts and warnings.

FINDING 7.1: The special teleconferences involving RFCs, WSFOs, NMC, and the Office of Hydrology during the 1993 flood event were beneficial in several aspects, especially to RFCs that were trying to consider future hydrometeorological conditions over their broad areas. Certain improvements, however, in the management and content of the teleconferences would have made them even more beneficial.	**RECOMMENDATION 7.1:** The logistics of handling and guidelines for the content of the teleconferences should be more streamlined by regional, NMC, Office of Meteorology, and Office of Hydrology personnel. The information on quantitative precipitation forecast products conveyed from NMC should have concentrated on additional physical insights into the forecasts, and their potential accuracies, beyond that contained in the issued products.
FINDING 7.2: NWS teleconferences did not use video.	**RECOMMENDATION 7.2:** The NWS should investigate the feasibility and evaluate the potential effectiveness of video teleconferencing during protracted events such as The Great Flood of 1993.
FINDING 7.3: In some cases, differences in RFC formats used to transmit river forecasts required editing by WSFOs and WSOs prior to issuance to the public.	**RECOMMENDATION 7.3:** All RFCs should use the same format in transmitting river forecasts and other products.
FINDING 7.4: Several internal NWS products, such as the State Forecast Discussion and Excessive Rainfall Discussion, were widely distributed to the media. In some instances, these technical products were taken out of context, sensationalized, and presented as official NWS forecasts by the media.	**RECOMMENDATION 7.4:** NWS Headquarters should complete a review of the policy on dissemination of internal forecast discussion products through the NOAA Family of Services.

7.2 EXTERNAL COORDINATION

As the NWS issues forecasts and warnings, those products are distributed in near real-time to a wide variety of Federal, state, and local agencies. Major cooperating agencies include the Federal Emergency Management Agency (FEMA), the U.S. Army Corps of Engineers (COE), and local and state EMAs.

In most cases during the flood, coordination between the NWS and other agencies was good. During the flooding, the NWS provided daily briefings on expected weather and flood conditions throughout the affected areas to FEMA's EOC in Washington, DC. This information was valuable in planning for the allocation and placement of additional resources. The Regional Hydrologist for the Central Region briefed the COE Vicksburg Division on a daily basis during the critical flood period. Nonetheless, the hydrologic situation at St. Louis is complex. There are three NWS RFCs that provide hydrologic forecasts for the region of the country covered by the St. Louis COE District Office. Consequently, the potential for internal inconsistency or confusion among the NWS forecasts exists. In an effort to minimize misinterpretation and facilitate interagency communication, EOCs were established in Kansas City, Minneapolis, Des Moines, and St. Louis, among other areas. Cooperating agency personnel suggested that during the flood event, interagency communication could have been enhanced by on-site NWS personnel available to provide rapid, clear interpretation of the NWS forecasts, warnings, and products. It was also suggested that ongoing cross-training of personnel would be very beneficial.

In a few cases, there was a lack of coordination between local EMAs and the NWS. There were several instances cited by local volunteer workers and residents where levees failed and local EMA officials failed to contact the NWS so that timely flash flood warnings could be issued.

Many Federal, state, and local agencies combined their efforts to establish EOCs in Kansas City, Minneapolis, Des Moines, and St. Louis. The centers were established to coordinate operations and disseminate information. The NWS provided a large amount of information to each center but had the staff resources to provide a full-time (8 hours per day), on-site, representative at only the Des Moines EOC continuously for a 2-week period in addition to other critical times during the flood event.

COE district offices routinely provided reservoir outflow data to the RFCs and to selected WSFOs, but COE officials expressed concern over problems and inefficiencies caused by interagency computer connections and slow transfer rates experienced with antiquated NWS computers and communication equipment. NWS personnel spent considerable time faxing NWS products to COE offices so the COE would receive the information faster. The COE and other cooperating agencies also noted frequent difficulty in accessing RFCs and WSFOs/WSOs through frequently busy commercial telephone lines.

Despite the recognized problem areas, much satisfaction with NWS performance and support was expressed by cooperating Federal, state, and local agencies. For example, the St. Louis Federal Aviation Administration (FAA) office expressed great satisfaction with the performance and information provided by WSFO St. Louis. That information allowed the FAA to remove much of their equipment from affected areas, such as Spirit of St. Louis Airport, to help prevent property loss.

At a national level, beginning in mid-July, the Meteorological Operations Division (MOD) of the NMC began extensive interactions with FEMA Headquarters and the Davenport, Iowa, office. MOD provided composite, 24-hour accumulated rainfall maps derived from RFC data files, latest forecasts, and special narrative discussions concerning the rainfall outlooks through 5 days, which was faxed to the Davenport office. MOD personnel participated in the daily briefing at the Washington FEMA office and provided a 5-7 minute presentation on the latest observed rainfall information and the latest forecast for the next 5 days. These briefings were also seen live by the White House Chief of Staff. Each day, information was assembled and faxed to the White House, FEMA Headquarters, and the Department of Agriculture at 8 a.m.; to FEMA in Davenport, Iowa, at 11 a.m.; to FEMA Headquarters and USDA at 3 p.m., with a different package to FEMA in Davenport also at 3 p.m.

FINDING 7.5: In some communities there appeared to be a lack of communication and coordination among different agencies within the same community and officials of adjoining communities. Critical river and flood forecast information needed to prevent damage to major facilities was sometimes unavailable to all agencies.	**RECOMMENDATION 7.5:** National, regional, and local NWS offices should team with Federal, state, and local agencies to coordinate more frequent communication to ensure that needed information is distributed among all agencies.
FINDING 7.6: County officials often failed to call the NWS when levees failed. In many cases, the media knew about failures before the NWS. For example, St. Louis emergency response teams, such as the Red Cross and Disaster Services, reported that some local officials were slow to report levee breaks to the local NWS office, which resulted in delays in the issuance of flash flood warnings by the NWS.	**RECOMMENDATION 7.6:** More intensive efforts should be undertaken at national, regional, and local levels to ensure maximum coordination and cooperation among agencies involved in disaster mitigation. While modernization and associated restructuring expansion of local staffs to include a Warning Coordination Meteorologist at each Weather Forecast Office should promote better coordination, immediate efforts are needed.

<u>**FINDING 7.7:**</u> EOC operations were established at several locations including Kansas City, Minneapolis, Des Moines, and St. Louis. These centers were staffed by key personnel from a variety of Federal, state, and local agencies involved in coordinating flood operations and disseminating information. WSFO Des Moines and the North Central RFC\WSFO Minneapolis maintained a periodic presence at EOCs through much of the flood event. Given the limited staffing available, it is out of the question for any NWS office to provide around-the-clock, on-site staffing support for EOCs. Although other WSFOs and RFCs provided information, they did not provide on-site representation at EOCs. In other cases where official EOCs were not established, close alliances were formed with the COE, the U.S. Geological Survey, and local officials, such as in North Dakota.	<u>**RECOMMENDATION 7.7:**</u> All WSFOs, RFCs, and WSOs should provide the highest level of support possible to EOC operations within their service areas during emergency situations. Highly reliable communications between the EOC and the WSFO/WSO/RFC is essential. When feasible, periodic, on-site EOC support should be provided. Such actions would improve coordination and cooperation in addition to increasing NWS visibility.
<u>**FINDING 7.8:**</u> The COE district offices generally provided reservoir outflow data on a periodic basis to the RFCs and to some WSFOs; however, the COE offices expressed concern over problems and inefficiencies in the connections and transfer rates experienced with antiquated NWS computers and communication equipment. The NWS, in some cases, had to fax products to the COE.	<u>**RECOMMENDATION 7.8:**</u> Over the short term, the NWS and COE should take all feasible actions to improve communications systems and data exchange procedures. Over the longer term, the NWS and COE should ensure that their respective RFC and water control district gateway systems are optimally interfaced.

FINDING 7.9: The Rock Island COE District strongly encouraged cross-training between COE and RFC personnel. Cross-training of NWS and COE personnel would substantially improve intra-agency and interagency operations, not only during flood events when personnel may be shifted from one office to another but also during routine operations.	**RECOMMENDATION 7.9:** See Recommendation 6.19.
FINDING 7.10: More timely and effective ways are needed for computer-to-computer exchange and dissemination of data and products, including graphic displays, between NWS field offices and their cooperators and end-users.	**RECOMMENDATION 7.10:** The NWS should actively pursue the multiple avenues required to provide timely products and information in appropriate formats to the various communities of end-users (see Recommendation 7.8). As part of this effort, NOAA/NWS should improve various aspects of its product dissemination policies.
FINDING 7.11: Certain cooperating agencies, especially the COE, noted frequent difficulty in accessing RFCs and WSFOs through commercial telephone lines.	**RECOMMENDATION 7.11:** The NWS should install additional, private telephone lines as required, if not on a permanent basis, then at least on a temporary basis during severe weather and flood events of this magnitude. The additional lines will help critical cooperators coordinate with NWS offices.
FINDING 7.12: Arrangements to handle NMC/MOD interactions with FEMA were accomplished largely on an ad hoc basis in response to the emergency situation.	**RECOMMENDATION 7.12:** NMC should establish a better level of understanding with other Federal agencies concerning what information can be provided on an emergency basis, how it should be provided, and who are the appropriate contact points.

<u>FINDING 7.13:</u> The National Flood Insurance Program, administered by the FEMA through the Community Rating System, encourages coordination among various local and regional agencies in the development of flood warning plans. Communities that qualify for participation in the Community Rating System receive discounts on flood insurance policy premiums throughout the community.	**<u>RECOMMENDATION 7.13:</u>** The NWS should encourage FEMA and the National Flood Insurance Program to strengthen recognition of community flood warning activities and to expand eligible activities to include comprehensive flood action plans. These flood action plans are designed to mitigate the impact of impending flooding, such as the identification of flood magnitude thresholds that trigger action (e.g., sandbagging) to protect critical facilities and infrastructure.

7.3 MEDIA CONTACTS

7.3.1 NATIONAL WEATHER SERVICE SERVICES TO MEDIA

Contacts were made by the disaster survey team with 12 media outlets in Minneapolis, Minnesota; Des Moines, Iowa; and Kansas City, Columbia, and St. Louis, Missouri; to evaluate NWS performance during The Great Flood of 1993. Included were metropolitan daily newspapers, television newsrooms and weather departments, radio station newsrooms and weather departments, and an Associated Press bureau office. The contacts were representative of media throughout the flooded area.

Media representatives were unanimous in their support of NWS efforts and were especially complimentary of the spirit of cooperation exhibited at local NWS field offices throughout the flood event. There was no media criticism of NWS actions, attitudes, or cooperation with media representatives. Some contacts mentioned minor changes they would like to see in products, but those proved to be the exception and did not negatively impact the NWS's ability to communicate with the public through the media.

Typical media comments are summarized:

> **Paul Douglas, Chief Meteorologist, KARE TV-11, Minneapolis:** *"Overall, I was very impressed with the timeliness and information provided; not just on the weather forecast side but on the river side as well."*

Jodi Chapman, Weather Reporter, WHO Radio, Des Moines: *"We've been very happy with the information given by the National Weather Service. Watches and warnings were timely and accurate.... We have a very good relationship with the National Weather Service. [Area Manager/Meteorologist in Charge] John Feldt is very easy to work with."*

John Carlson, Reporter, Des Moines Register: *"The most important aspect for [reporters] is the ability to get an update or an interview.... [WSFO Des Moines] did a very good job in providing us with information during the flood. We usually called two or three times in the afternoon, and they were always responsive and helpful."*

Brian Bracco, News Director, KMBC TV-9, Kansas City: *"I thought your guys were on the ball every step of the way. I've found they bend over backward even when up to their ears with forecasts. I think [Warning Coordination Meteorologist] Bill Bunting and the whole crew is highly professional. It makes our job a lot easier working with those guys giving us the support they did."*

Tim O'Neal, Reporter, St. Louis Post-Dispatch: *"The information seemed to hold up pretty good, even when there were lots of updates because of the continued rain. The numbers always seemed to be within a few inches of what levels were reached."*

Tom Langmeyer, Program Director, KMOX Radio, St. Louis: *"We relied heavily on [Service Hydrologist] Jack Burns for information. We had very good cooperation on getting information on river stages, as well as weather and other conditions. There was generally great cooperation by the NWS."*

Scott Connell, Chief Meteorologist, KSDK TV-5 St. Louis: *"The WSFO was very cooperative, in particular Jack Burns. Overall, the office put out excellent statements included with evacuation warnings and safety rules."*

All of the WSFOs, WSOs, and RFCs in the affected areas, as well as NWS Headquarters and NMC, reported higher levels of media inquiry than previously experienced. All offices received numerous calls from media from around the country, and several received calls from media in England, Japan, Austria, Canada, and Venezuela. At the local level, whenever possible, media calls on the flood were handled by the Service Hydrologists. The huge volume of calls, however, necessitated that all forecast staff members and technicians assist in handling media requests. In addition, several times per day, the MOD handled requests for interviews by National Public Radio. These were used extensively by many radio stations. These telephone interviews typically included both the latest observed information and the forecasts.

At various times, WSFOs, WSOs, RFCs, the Regional Hydrologist, and the Public Affairs offices were inundated with numerous media queries. The sheer volume of incoming telephone calls severely overtaxed the public relations capabilities of all offices involved. On one occasion at the North Central RFC and on another at WSFO Des Moines, media calls were so pervasive during critical severe weather and flooding incidents that the local managers sought external assistance in handling the heavy media activity. The Central Region Public Affairs office advised the managers to issue special media advisories stating that only emergency telephone calls could be answered until threatening situations passed. This action allowed forecasters to devote full attention to potentially severe situations and to provide accurate and timely updates.

Precipitation comparisons compiled from climate summary products were distributed on a daily basis and proved to be greatly appreciated by the media. Weather and river forecast updates were frequently requested by area media. Print media in distant locations made numerous requests for basic flood and weather background information. Because of the long duration of The Great Flood of 1993, additional resources to help handle public affairs functions would have been helpful. Agency-wide staff shortages prevented temporary staffing actions from being taken. Additional training on interaction with the media and other external parties would have been beneficial to shorthanded staffs that had been working long hours under high stress. The vast area of flooding prevented implementation of a single-point (regional) contact to handle media calls regarding the flood.

While the media were highly complimentary of NWS cooperation and the high level of information provided, some did suggest ways in which timely coordination could be improved. One suggestion to help broadcasters meet public demand for early, daily information was for better coordination of river stage information and flood forecast product issuance with broadcast schedules. This would allow radio and television meteorologists to receive such products with sufficient time to tailor them for specific audiences.

<u>FINDING 7.14:</u> The magnitude of The Great Flood of 1993 made the central United States the focus of national and worldwide attention, which led to intense media interest. The volume of telephone media queries for critical and noncritical flood information overtaxed NWS staff at national, regional, and local levels. All offices in the affected areas were inundated with requests to provide interviews, material, and information to the media and NWS Headquarters for input to congressional briefings and for other program exercises.	<u>RECOMMENDATION 7.14:</u> Because of the long duration of The Great Flood of 1993, additional resources to help handle public affairs functions should have been available. A plan for activation of additional public affairs personnel support for such events should be developed. Additional training on procedures for interaction with the media and other external parties should be provided for some offices.

FINDING 7.15: Some media members suggested that better coordination of the NWS product release times to coincide with the broadcast schedules would have allowed for more timely and effective broadcast of NWS products to the public.	RECOMMENDATION 7.15: The NWS should continue all possible acceleration of modernization and associated restructuring components including lengthened standard hours of operation, staff augmentation, and implementation of new technologies at RFCs, which should allow initial morning river forecasts to be issued in the 7 a.m. time frame.

7.3.2 OTHER AGENCY MEDIA CONTACTS

Much of the flood information to the media was provided by personnel from other government agencies and private services. The COE; state, county, and city EMAs; FEMA; river authorities; and other agencies were in frequent contact with the media. The large number of "officials" providing information in interviews at times caused some public confusion because of the different data sets and terminology used. The private agencies generally deferred questions on flood forecasts and left that up to NWS personnel.

The overall media attitude appears to have been one of cooperation with both NWS and private sources. One reporter noted that because his newspaper did not subscribe to the NOAA Weather Wire Service (NWWS), it forced reporters to contact the NWS more frequently than would have been necessary with NWWS to provide information.

7.4 DIRECT USER SERVICES

The survey team found substantial differences in the levels of public interaction and direct individual service provided by the various NWS offices in the flood-affected areas. These differences were caused largely by differences in staffing, geography, and other local differences, as well as the availability of river authorities and emergency preparedness agencies to deal with the public. Obviously, user satisfaction was greatest in those instances where the NWS had the resources to provide greater personal contact.

Information provided by the NWWS was valuable; in some instances, however, local government agencies said they would like to have the service but cannot afford its high cost. Currently, many local EMAs receive weather warnings through their state crime networks. Weather warnings, however, are not given high priority on these systems. Sometimes they are received long after the warning has been issued. These networks tend not to carry statements or other information that would be very useful in the operations of EMAs. In the interest of public safety, many NWS offices spent valuable time faxing crucial information that is available on NWWS but not through state crime information networks to various county EMAs.

NOAA Weather Radio (NWR) provided a useful source of direct contact between the NWS and users. Virtually all radio and television stations contacted used NWR as a backup information source to NWWS. The effectiveness of NWR to the public was limited. Even though NWR broadcasts were available in almost all areas impacted by the flooding, much of the public remains unaware of its existence. An occasional problem was discovered in areas where NWR was used by the public. Users noted that some flood forecasts broadcast on NWR were out of date and that some river forecasts did not specify the time of observed stages.

Many NWS offices faxed graphics to state EMAs. This included 24-hour rainfall and quantitative precipitation forecasts for the 24- and 48-hour periods. Many EMAs stated that this information proved very valuable. They would like to see a system developed by which they could receive graphical guidance on a regular basis. They also expressed an interest in receiving continuous radar imagery. Some county EMA directors said they had investigated the possibility of subscribing to the NEXRAD Information Dissemination System (NIDS), through which radar imagery will be provided in the modernized NWS, but found it too expensive for small county budgets.

FINDING 7.16: In many instances, local communities and municipalities are not making effective use of the NWWS. In some cases, agencies were not even aware of the existence of the NWWS. Many communities did not use NWWS because of: (a) the high cost of the service, (b) the need for tailored forecast information, and (c) the high volume of products disseminated.	**RECOMMENDATION 7.16:** The NOAA/NWS should explore the possibility of lowering NWWS costs, study the ramifications of not lowering NWWS costs, and redouble efforts to make other agencies aware of NWWS availability and features. Additional sources of product distribution, such as Internet, should be explored. Also, NOAA should encourage FEMA to provide support and assistance to communities so they can subscribe to the NWWS.
FINDING 7.17: Most of the public is unaware of the availability of NWR, even though it broadcasts across most of the United States.	**RECOMMENDATION 7.17:** The NOAA/NWS must make a substantially greater effort to educate the public on the availability of NWR and of the life-saving service it provides.

<u>**FINDING 7.18:**</u> Broadcasts of flood forecasts on NWR were sometimes not up to date. Some river products did not specify the time of the observed stage. It is especially critical during epic weather and flood events, such as The Great Flood of 1993, that personnel at NWS offices take extra steps to ensure that information broadcast on NWR is updated frequently so that NWR listeners receive only the latest information.	<u>**RECOMMENDATION 7.18:**</u> The current NWR policy of broadcasting the time and date for specific observations should be adhered to. See Finding and Recommendation 5.36 pertaining to more frequent forecasts and updates.
<u>**FINDING 7.19:**</u> Weather radar imagery and graphic products were not available to most Federal, state, and local agencies.	<u>**RECOMMENDATION 7.19:**</u> The NWS should determine whether current and planned provisions for dissemination of weather radar products are adequate to meet the needs of NOAA cooperators throughout the Nation.
<u>**FINDING 7.20:**</u> Some county EMAs stated that the cost of becoming a NIDS subscriber exceeds financial resources of many county EMA offices, especially in counties with small populations.	<u>**RECOMMENDATION 7.20:**</u> The Federal Government should ensure that the NIDS providers continue to offer lower cost capability for these counties. The local WSFOs should also continue emergency coordination with county EMAs.

CHAPTER 8

PREPAREDNESS AND USER RESPONSE

8.1 INTRODUCTION

The National Weather Service (NWS) and state and local governments and communities work together to prepare for and deal with the consequences of meteorological and hydrological disasters. The agency maintains a warning and preparedness program to coordinate and expand this effort. There are two important elements in preparing the public to minimize or eliminate the weather's impact. First, information about the event must be communicated or disseminated to those at risk. Second, dissemination of information that encourages the public to respond appropriately is critical. For the communication process to succeed, it is critical for officials to notify the public so those at risk can take the proper steps to protect themselves and their property.

8.2 INTERNAL PREPAREDNESS

The effectiveness of NWS information is only as good as the proficiency of the NWS staff to monitor weather conditions, detect severe storms, evaluate conditions, and issue appropriate forecasts or warnings. Realistic drills for all operations personnel should be a part of every office's internal preparedness program. Drills should include all phases of office emergency operations for all events that threaten the area of responsibility.

Internal drills are conducted on floods and flash floods by all NWS Central Region Forecast offices. The offices are routinely required to ensure that critical maps, data sets, and basin overlays are available that accurately depict the hydrologic information in their respective areas of interest. In spite of these efforts, some offices were still hampered by not having suitable base maps to appropriately carry out their functions. An important tool for hydrologic forecasters is a current, updated set of topographic maps depicting the current geographic information in the forecast offices' areas of responsibility.

NWS offices are staffed for most weather situations, but the severity and length of this flood made it difficult for personnel to handle the additional workload. During the flood event, 19 NWS hydrologists were reassigned to provide assistance at Weather Service Forecast Offices (WSFO) and River Forecast Centers (RFC) in affected areas. There is, however, no official national or regional policy for reassignment during long-term, weather-related emergencies. In some cases, NWS personnel were at training during the event; there is no official policy for recalling employees back to their duty stations during extreme weather emergencies like The Great Flood of 1993.

FINDING 8.1: Some basin and topographic maps at WSOs were outdated or missing.	**RECOMMENDATION 8.1:** Offices in need of topographic maps should procure them directly from the U.S. Geological Survey. NWS Headquarters and regional offices should establish procedures to generate and update WSFO basin maps.

8.3 EXTERNAL PREPAREDNESS

It is vital that NWS personnel share knowledge of dissemination systems, procedures, capabilities, and response requirements with the media; Federal, state, and local agencies; and the general public involved in the total warning process.

As part of this effort, NWS field offices are responsible for managing warning preparedness programs in their areas with one person in each WSFO acting as the key contact with emergency management officials, the media, the public, and other agencies. Of the nine WSFOs affected by the flood, three have Warning and Coordination Meteorologists (WCM), and six have Warning and Preparedness Meteorologists (WPM).

WPMs/WCMs develop extensive networks of trained spotters to report severe weather in their areas. Audio-visual and printed materials are used to train these spotters. In the nine-state region hardest hit by the flood (Illinois, Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, South Dakota, and Wisconsin) dense networks of nearly 18,000 weather spotters exist. These spotter networks maintained effective coordination efforts throughout the flood event. Few of these spotters, however, were recruited or trained to report floods. In fact, few have rain gages. While the spotter networks were able to continue operations, except in instances where spotters were personally impacted by the flood, additional training and participation in precipitation and flood reporting could have made their contributions even more effective and significant.

Benefits of community or statewide drills with Federal, state, and local agencies to improve knowledge of weather hazards and to evaluate current communications systems and procedures are immeasurable. Throughout the Midwest, state drills on severe weather preparedness are conducted at least once a year.

An effective warning preparedness program depends on frequent contact and coordination with Emergency Management Agencies (EMA). NWS offices may need to strengthen coordination with local and state EMAs. During the flood itself, the quality of coordination among the NWS and EMAs varied. In some locations, EMA personnel did not effectively communicate vital river information to the NWS, leading to delays in the issuance of flood and flash flood warnings. In other locations, working relationships among these entities was excellent and led to faster dissemination of warnings.

County emergency officials expressed general satisfaction with NWS services and coordination. Some local EMAs noted occasional confusion caused by different statements made by the NWS and the U.S. Army Corps of Engineers (COE). Because COE representatives were often on-site at Emergency Operation Centers (EOC), levees, and flood-threatened areas, local authorities often used information on stage levels and expected crests that was provided by the COE rather than using NWS statements and forecasts levels. On-site NWS representation, especially at EOCs, would have improved coordination efforts, helped alleviate confusing or contradictory information, and made the public more aware of the active NWS involvement.

NWS access to flood operation manuals for emergency management and water facility departments in major municipalities could have improved the response to forecast and warnings. These manuals provide information for decision makers based on river stages.

The size and sophistication of local EMAs, along with the availability of state-of-the-art communications equipment, also had an impact on effective cooperation and coordination between the NWS and the EMAs. Obviously, computer-equipped offices were better prepared to process and act on information provided by the NWS. Most up-to-date EMAs were located in large cities, although there were exceptions. For example, St. Charles County, Missouri, (located adjacent to St. Louis) has a relatively small population but maintains a modern EOC that employs a computer-based Emergency Information System that provides EMA officials with critical hydrometeorological information. Redundant, advanced communications systems connect the EOC with other emergency agencies and the NWS. Coordination efforts between St. Charles County EMA and the NWS were excellent through the course of the flood. EMA officials noted that St. Charles County had made a commitment to implement the best emergency operations system and equipment available. Private sector funding was solicited and secured to help the county supplement its emergency operations budget. Similar efforts could be beneficial to emergency managers in other areas.

FINDING 8.2: County emergency management officials expressed general satisfaction with NWS services. They sometimes noted a difference between statements issued by the COE and the NWS. Often, since the COE had a physical presence at the flood site, local authorities used information provided by the COE.	**RECOMMENDATION 8.2:** The NWS should improve coordination with county and state EMAs and EOCs through periodic review of action plans, participation in mock disaster exercises, and other planning approaches. Improved real-time coordination between the NWS and EOCs is addressed in Recommendation 7.7.

<u>FINDING 8.3:</u> Most public works and emergency management departments in major municipalities have flood operation manuals. These manuals contain information on critical decision points for which various actions are initiated once critical river stages are reached (or forecast). These manuals were not always available in some NWS field offices.	<u>RECOMMENDATION 8.3:</u> The NWS should obtain the flood operation manuals, as well as maintain and improve relationships with respective public works agencies and EMAs. Relevant information from these manuals should be incorporated in the Service Hydrologist Information Management System.
<u>FINDING 8.4:</u> St. Charles County, Missouri, which has a moderate population, maintains a modern EOC operating a state-of-the-art Emergency Information System. Private sector funding helped to build an advanced EOC that uses NWS warnings and forecasts to better serve the public.	<u>RECOMMENDATION 8.4:</u> Federal, state, and local agencies are encouraged to coordinate and to expand this type of modernized emergency system nationwide. This would improve dissemination and increase efficiency of providing NWS information to the public.

8.4 PUBLIC AWARENESS OF AND RESPONSE TO NATIONAL WEATHER SERVICE RIVER FORECAST SERVICES

In most cases, flood forecasts were provided with sufficient lead-time to allow residents to prepare for the event, although greater lead-time clearly would have contributed to improved mitigation actions in many instances. Statements, watches, and warnings provided "call-to-action" information instructing the public on the proper safety procedures.

Extensive media coverage of the event heightened public awareness of the severity and danger of The Great Flood of 1993. While general public awareness was high, there was some confusion among the media and the public as to the specific meaning of NWS flood statements, watches, warnings, and forecasts. Such confusion could prove detrimental to future effectiveness of NWS warning efforts.

Dissemination of flood forecasts was generally rated good to excellent by those receiving the information. Virtually all individuals and media outlets interviewed by the survey team concerning flooding of the Mississippi and Missouri Rivers and their tributaries were pleased with the products provided by the NWS. Much of the public was unaware that forecasts and statements originated from the NWS, crediting them rather to the COE, the electronic media, etc.

The numerous NWS precipitation reports, flash flood and flood advisories, and river forecasts undoubtedly saved lives and prevented tens of millions of dollars in damages as business owners, farmers, homeowners, and others responded in a timely fashion to reduce losses by floodproofing property, fortifying levees, and moving equipment, livestock, and machinery. Unfortunately, the survey team was not able to provide a credible estimate of damages averted because of NWS forecasts. A research project to investigate the cost savings resulting from the NWS forecasts and warnings associated with The Great Flood of 1993 could benefit the NWS and be of interest to the disaster preparedness community.

It was disclosed that a few agricultural users of NWS flood forecasts and river stage information tended to discount the accuracy of those products. Although forecast river stage levels were reasonably accurate, one agricultural user in St. Charles County stated that he and others mistakenly thought that stage forecasts were exaggerated. This perception sometimes resulted in less-than-adequate protective measures being taken by some agricultural users. A strong, post-flood effort by NWS offices to work with local media to inform the public of the complexities involved in predicting and following the crests of such large floods could result in positive public reaction and increased awareness of NWS efforts and responsibilities.

<u>FINDING 8.5:</u> The media and the public do not fully understand hydrologic terminology, procedures, and forecast products.	<u>RECOMMENDATION 8.5:</u> The NWS and NOAA Public Affairs, at all levels, should develop a public education program to increase awareness of and understanding about the hydrology program by using brochures, news releases, fact sheets, and other background materials, along with increased interaction with the media.

CHAPTER 9

SUMMARY OF FINDINGS AND RECOMMENDATIONS

9.1 GENERAL DESCRIPTION OF THE EVENT AND ITS IMPACT (CHAPTER 1)

No findings and recommendations.

9.2 MAJOR LESSONS LEARNED AND OPPORTUNITIES FOR THE FUTURE (CHAPTER 2)

FINDING 2.1: The meteorological, climatological, hydrological, and hydraulic conditions that converged to produce The Great Flood of 1993 were unique in many aspects. Initial assessments of the economic impact of The Great Flood of 1993 indicate that losses will range between $15-20 billion. This is the single, greatest flood loss in the Nation's history and rivals Hurricane Andrew in overall losses. The extent of social disruption is beyond measure.

RECOMMENDATION 2.1: The National Oceanic and Atmospheric Administration (NOAA) should work closely with its many collaborators to encourage further investigations into the various aspects of The Great Flood of 1993. Much is left to be learned. Additional scientific studies should be conducted to provide important insights on how to further minimize losses from future disastrous floods.

FINDING 2.2: There were major benefits, as well as some problems, related to the many uses of National Weather Service (NWS) flood forecasts. The disaster survey team was unable to assess comprehensively the impact of the hydrologic forecasts and products due to the limited duration of the survey. Because of the large socioeconomic impacts of this historic flood event and the potential mitigating effects of higher-quality hydrologic forecasts, a more detailed post-flood impact analysis would be invaluable.

RECOMMENDATION 2.2: NOAA should support a comprehensive, external study to evaluate and quantify the benefits derived from hydrologic forecasts. This study should take maximum advantage of the lessons learned during The Great Flood of 1993.

FINDING 2.3: A large suite of software and hydrologic procedures, especially National Weather Service River Forecast System (NWSRFS), is critical to current River Forecast Center (RFC) operations and even more critical to future operations. There is significant concern about maintaining the required depth of expertise and support at both the field and headquarters levels required for this complex system.

RECOMMENDATION 2.3: The NWS Office of Hydrology should systematically evaluate the operational readiness of NWSRFS and other software used in hydrologic forecasting.

FINDING 2.4: RFCs do not routinely store river and flood forecast information and products in digital form. Similarly, the National Meteorological Center (NMC) does not routinely archive quantitative precipitation forecast (QPF) products in digital form. These data and forecast products are critical for post-event analyses, research and development, model calibration, extended streamflow prediction and simulation requirements, climatological studies, and forecast verification.

RECOMMENDATION 2.4: Routine procedures must be implemented at the NMC and the RFCs, as part of modernized system capabilities, to archive all data and products in digital format that are pertinent to ongoing developmental, operational, and verification programs.

FINDING 2.5: Although only nine Weather Surveillance Radars 1988 Doppler (WSR-88D) had been installed for areas covering parts of the flooded states, several instances illustrated the revolutionary impact the WSR-88D will have on flood and flash flood forecasts and warnings. One especially noteworthy example occurred on July 18, 1993, when the Chicago WSR-88D accurately mapped a 4.0- to 6.6-inch rainfall core that led to a warning being issued prior to significant flooding. Greater lead-time could have been provided, however, if the flash flood potential (FFP) algorithm had been implemented in the WSR-88D Radar Product Generator.

RECOMMENDATION 2.5: Every effort must be made to keep the NWS modernization on schedule and to accelerate its implementation and operational support. It is imperative that the change-management process for the WSR-88D program be streamlined so that it does not take a year, or longer in some cases, to get critical software changes or enhancements implemented--the FFP algorithm being a case in point. Furthermore, Advanced Weather Interactive Processing System (AWIPS)-type capabilities must be installed at the RFCs to use effectively WSR-88D rainfall estimates for numerical input to hydrologic models.

FINDING 2.6: Weather Service Forecast Offices (WSFO) in the affected area have headwater tables for selected basins that are used to provide flash flood guidance. Nonetheless, many offices felt a need for more advanced, local river forecast procedures to produce headwater forecasts systematically or to update RFC forecasts. This was especially critical in situations in small river basins where hydrometeorological conditions changed rapidly.

RECOMMENDATION 2.6: NWS national and regional headquarters, NWS field offices, and the Forecast Systems Laboratory of the Office of Oceanic and Atmospheric Research should accelerate development of the Weather Forecast Office (WFO) Hydrometeorological Forecast and Warning Subsystem for incorporation into the AWIPS application software suite.

FINDING 2.7: The modernized NWS has a critical need for professional personnel trained in both hydrology and meteorology and has developed qualification criteria for these new hydrometeorologists.

RECOMMENDATION 2.7: NWS and NOAA managers and personnel offices must ensure that personnel, recruitment, qualifications, and promotion processes appropriately reflect requirements for hydrometeorologists.

FINDING 2.8: The effectiveness of the NWS's river forecasting services critically depends on other Federal, state, and local agencies for (1) information used in the forecasting process, (2) the dissemination of forecasts and warnings, and (3) ensuring that the public take actions necessary to prevent loss of life and to mitigate damage.

RECOMMENDATION 2.8: The NWS needs to maintain and strengthen cooperative arrangements with current partners and to seek additional opportunities to work with interested parties to ensure the protection of life and property.

FINDING 2.9: Currently, RFCs typically issue stage forecasts for only 1, 2, and 3 days into the future at most forecast points and crest forecasts out to about 1 week for a few selected forecast points. Federal, state, and local groups indicated a need for increased lead-times for hydrologic forecasts. Many expressed the need for a range of forecast stages with associated probabilities of occurrence.

RECOMMENDATION 2.9: The Federal Government should press forward with implementation of the Water Resources Forecasting System (WARFS) which will provide the required capabilities.

FINDING 2.10: QPFs are not being used directly, objectively, and systematically in hydrologic modeling in Central Region RFCs. In addition, not all WSFOs have appropriate software and computer equipment to issue QPF forecasts for the RFCs. Many users understand that QPF products have inherent uncertainties. Nonetheless, many expressed a need for probabilistic river forecasts that incorporate QPFs.

RECOMMENDATION 2.10: If Recommendations 2.6 and 2.9 are implemented, they will also satisfy the requirements to include QPF information in hydrologic forecasts. The NWS should continue to support scientific efforts aimed at producing probabilistic QPFs at WSFOs and Weather Service Offices (WSO) through support of training and research initiatives.

FINDING 2.11: The extensive flooding of 1993 has created large regions with above-normal soil moisture conditions across the Upper Midwest. Consequently, fall rains and spring snowmelt in 1994 may substantially elevate the potential for flooding. There is a need for immediate and extended assessments of flood potential persisting through at least the spring of 1994. Special hydroclimatological assessments done monthly would be valuable.

RECOMMENDATION 2.11: The NWS Office of Hydrology and the Central Region should provide early and ongoing assessments of potential spring flooding in 1994 in the areas affected by The Great Flood of 1993. This effort should draw on early experiences from the NWS modernization and pilot WARFS activities wherever possible. Additionally, information and data from the Midwest Climate Center and NMC's Climate Analysis Center should be used to support an ongoing assessment of soil moisture conditions and potential future flooding across the Upper Midwest. Moreover, the NWS should support an enhanced airborne soil moisture data collection program during the late fall of 1993 and a comprehensive airborne snow water equivalent data collection program during the winter of 1993-94 over the region affected by The Great Flood of 1993.

9.3 HYDROMETEOROLOGICAL SETTING (CHAPTER 3)

FINDING 3.1: The duration and magnitude of The Great Flood of 1993, as well as its antecedent conditions, strongly support the premise that this event was a significant climate variation rather than simply a sequence of meteorological incidents.

RECOMMENDATION 3.1: Additional analyses of this situation, by both research and operational communities inside and outside of the NWS, should be encouraged. The Great Flood of 1993 should be considered as a climate time-scale variation or anomaly, which may be attributable to a combination of atmospheric, oceanic, and land factors, such as circulation, temperature, soil moisture, and their complex interactions.

FINDING 3.2: The soil moisture models for the Midwest, operated by the Midwestern Climate Center, can provide a constantly updated assessment of regional soil moisture conditions and a probability of future soil moisture potential critical to an evaluation of longer-term flood potential. In addition, the High Plains and Northeast Climate Centers also provide soil moisture information.

RECOMMENDATION 3.2: The NWS and, in particular, the RFCs should obtain soil moisture information from the Regional Climate Centers to enhance near real-time monitoring of hydrologic conditions and to guide preparation of flood potential outlooks. The remaining Regional Climate Centers should be encouraged to consider providing soil moisture information.

9.4 HYDROLOGIC AND HYDRAULIC FORECAST METHODOLOGY (CHAPTER 4)

FINDING 4.1: Accurate river gage and other information reported on NWS Form E-19 is critical to hydrologic forecast techniques and procedures. The severe flooding of both the Mississippi and Missouri Rivers and their tributaries will necessitate updating much existing E-19 information.

RECOMMENDATION 4.1: The Regional Hydrologist, Area Managers, Hydrologists in Charge, and Service Hydrologists (SH) should coordinate with the U.S. Army Corps of Engineers (COE), the U.S. Geological Survey (USGS), and other agencies to research, verify, and update river stage levels and other information required by Form E-19 at all affected reporting points.

FINDING 4.2: The number of sites where backwater or loops in ratings affected forecasts was unprecedented.

RECOMMENDATION 4.2: Loop rating curves are an indication that a dynamic wave routing technique is required. Each RFC and the Office of Hydrology should investigate the input data, model calibration, and simulation results associated with implementation of a dynamic wave model in any affected area.

FINDING 4.3: In many of the flooded areas on the Missouri and Mississippi Rivers, the stages exceeded those of prior records while the corresponding volumes of flow often did not. Assessment of the causes of this factor are important to the objective of applying the best river hydraulics in future river modeling and forecasting.

RECOMMENDATION 4.3: In The Great Flood of 1993, levee effects and unknown ratings are probably the dominant causes of discrepancies between the river stages and volumes of flow. The Hydrologic Research Laboratory should use the dynamic wave model to determine the causes for these discrepancies. Additionally, new ratings must be established for many forecast points.

FINDING 4.4: Levee effects on overbank storage and downstream forecasts were difficult to analyze. The size and type of failures were highly variable.

RECOMMENDATION 4.4: The use of airborne photographic reconnaissance to pinpoint levee failures should be an option readily available to RFCs. The Hydrologic Research Laboratory and the RFCs should investigate more effective ways to model levees and levee failures.

FINDING 4.5: St. Louis District COE has profiles of Federal levees with top-of-levee elevations for non-Federal levees. Some levee profiles may change in the aftermath of the extensive flooding.

RECOMMENDATION 4.5: The NWS should coordinate with the COE to obtain levee information for use in forecast procedures, especially when implementing the dynamic wave model in areas affected by the flood.

FINDING 4.6: Coordination between the Missouri Basin River Forecast Center (MBRFC) and the North Central River Forecast Center (NCRFC) for the Missouri River forecast at Hermann, Missouri, was critical. Attempts to coordinate over the telephone were somewhat successful, but much of the information exchange was hampered by technological limitations. Limitations in the current RFC technology do not allow the Hermann forecaster at the MBRFC and the St. Louis forecaster at the NCRFC simultaneously to view all of the graphic and hydrologic information (including WSR-88D, hydrograph, satellite, and derived data sets) used by the other forecaster as input to his/her forecast procedures.

RECOMMENDATION 4.6: The NWS should aggressively pursue installation of AWIPS and AWIPS-type facilities at RFCs (see Recommendation 4.10, 5.15, and 5.16) required to support the modernized NWSRFS, the Interactive Forecast System, and inter-RFC communications.

FINDING 4.7: Portions of the Mississippi and Missouri River basins have many complex hydrologic and hydraulic elements that require application of advanced modeling approaches to handle such effects as backwater at river junctures, overbank flows, levee failures, and changing ratings.

RECOMMENDATION 4.7: The RFCs and the Office of Hydrology should accelerate the implementation of the dynamic wave routing model on those river reaches where its capabilities are required.

FINDING 4.8: Detailed Geographic Information Systems (GIS) would have helped in the design and calibration of some hydrometeorological procedures, as well as allowing for more site-specific delineation of flood occurrences.

RECOMMENDATION 4.8: NWS Headquarters should carefully examine plans for use of GIS applications within the AWIPS program to assure the most effective use of this technology to assist the national hydrology program.

FINDING 4.9: Current limitations in operational implementation of hydrologic/hydraulic models, computer hardware, and software contributed to the inability of the RFCs to incorporate QPF amounts into river forecasts on an objective, routine basis.

RECOMMENDATION 4.9: The RFCs should move as quickly as possible to implement advanced hydrologic/hydraulic models and planned, modernized methods to objectively and routinely incorporate QPF. Since these planned methods require AWIPS-type technology, the RFCs should also investigate ways in which QPFs may be objectively incorporated into the river forecasts in the near term (see Finding 2.10 above) without damaging the integrity of the forecast (e.g., issuing a banded forecast based on potential rainfall).

FINDING 4.10: The forecasters and end-users expressed frustration with the limited amount of information contained in the river forecasts. Sufficient information is not provided to do a proper risk analysis. Forecasters compute total hydrographs and have some feel for the potential effects of various hydrologic contingencies, such as levee failures and rating shifts. There is currently no way routinely to convey this additional information to the sophisticated end-users capable of benefiting from the added information.

RECOMMENDATION 4.10: As soon as possible, the NWS should: (1) install AWIPS and AWIPS-type equipment at the RFCs (see Recommendation 4.6, 5.15, and 5.16) and (2) implement WARFS to provide the required hydrologic forecast capabilities (see Recommendation 2.9).

9.5 DATA ACQUISITION, TELECOMMUNICATIONS, FACILITIES, AND COMPUTER SYSTEMS (CHAPTER 5)

FINDING 5.1: Most NWS offices indicated that a shortage of stream and precipitation gages hindered their ability to produce accurate and timely forecasts. The Des Moines case study in Chapter 6 dramatically illustrates the major impact that the loss of just one stream gage can have on hydrologic forecast procedures.

RECOMMENDATION 5.1: NWS field offices should continue to provide support to cooperating agencies in their efforts to obtain resources for the maintenance of existing gages and the installation of additional stream and precipitation gages in strategic locations.

FINDING 5.2: There were a number of errors in Standard Hydrometeorological Exchange Format (SHEF)-coded data.

RECOMMENDATION 5.2: The Office of Hydrology and regions should increase the emphasis on training in the use of SHEF for data exchange. Additionally, the NWS should increase the use of automated, quality-control procedures for data entry including those appropriate for Remote Observation System Automation (ROSA).

FINDING 5.3: The number of stations in the NWS cooperative program has been declining. There is a need to recover lost stations.

RECOMMENDATION 5.3: Local NWS offices should explore ways to enhance their cooperative programs. The importance of the Cooperative Observer Program should be stressed to all current and prospective members of the cooperative network.

FINDING 5.4: Most offices would like to see the ROSA system expanded to include more cooperative stations.

RECOMMENDATION 5.4: Advantages of ROSA should be emphasized, and NWS should fund increased deployment of ROSA systems.

FINDING 5.5: RFCs and WSFOs found the data collection platform (DCP) river stage data to be generally useful; but cases were noted when significant formatting, decoding, and other errors occurred. One RFC felt that rainfall information from tipping bucket gages was so unreliable as to be unusable with current quality-control procedures. Consequently, the DCP precipitation data in the RFC's area were not used in the river and flood forecasts.

RECOMMENDATION 5.5: DCP data should be carefully scrutinized daily. When errors are detected, the agency owning that particular DCP should be contacted immediately. If the problem is not corrected within a reasonable time, proactive, follow-up contacts should be made when time permits. RFCs should improve their capabilities to display, verify, and quality control DCP rain gage data automatically to make maximum use of this valuable data source.

FINDING 5.6: Once transmitted, DCP data take too long to reach the RFC and WSFO databases.

RECOMMENDATION 5.6: NWS must ensure that the increased computing capabilities planned as a part of NWS modernization include adequate telecommunications and a robust data management system to alleviate these problems. The NWS should implement Automated Critical Reports in Hydrometeorological Automated Data System (HADS) as soon as possible to help alleviate this problem.

FINDING 5.7: In one instance, the RFCs had difficulty receiving data from HADS. The problem stemmed largely from the imprecise specification of the Time Periodic Report capabilities and occurred when retrieving COE DCP data from the Rock Island District.

RECOMMENDATION 5.7: The NWS should provide an in-depth training program to HADS focal points at RFCs and WSFOs. The NWS should implement Automated Critical Reports in HADS to facilitate data transfer.

FINDING 5.8: Some NWS Limited Automatic Remote Collectors (LARC) were unable to report data when the river stage exceeded 32.7 feet. The data register in a LARC can accept and report information from a total of 32,767 increments. If the decimal point is set to read out to one thousandth of a foot, the unit has a range of only 0.000-32.767.

RECOMMENDATION 5.8: Electronics Technicians should program LARCs so that they can accept and report data only to the nearest one hundredth of a foot (resulting in a total range of 00.00-327.67 feet). Electronics Technicians should also set up all appropriate LARCs so that the data range is broad enough to cover well beyond the greatest flood of record, as well as below the lowest low flow on record. The NWS Training Center should provide the necessary training to program and set up LARCs.

FINDING 5.9: Information obtained from LARCs demonstrably increased the ability of forecasters to issue accurate and timely forecasts and warnings.

RECOMMENDATION 5.9: High priority should be placed on the installation and maintenance of additional LARCs with attached, automated rain gages. The NWS should place a high priority on the Equipment Replacement Program needed to restore, to maintain, and, in some strategic locations, to add LARCs required to support the NWS hydrology program.

FINDING 5.10: Currently there are two Centralized Automatic Data Acquisition System (CADAS) computers. System A collects data from LARCs located in the Eastern and Central Regions, and System B collects data from LARCs located in the Southern and Western Regions. Each system is currently designed to collect data from 510 LARCs. System A presently collects data from 503 LARCs, and System B presently collects data from 350 LARCs. A better balance between the two systems may be possible to ensure that System A has room for more than the seven free spaces that now exist.

RECOMMENDATION 5.10: CADAS should be modified to collect data from more LARCs. Additionally, the CADAS interrogation programs should be updated to include newer telemetry systems such as Sutron 8200 data loggers with modems and Campbell CR-10 recorders. The NWS regions and the Office of Hydrology should establish an advisory board to recommend to the CADAS Program Manager appropriate modifications to the CADAS required to support the NWS hydrology program.

FINDING 5.11: Stream gage observations from multiple gages at single locations sometimes created confusion.

RECOMMENDATION 5.11: NWS policy should clearly designate the primary and secondary gages at those sites where multiple gages exist.

FINDING 5.12: In many cases, stream gages are mounted on the downstream side of piers and bridge pilings. At high flows, drawdown effects may lead to errors and inconsistencies in stage observations.

RECOMMENDATION 5.12: In a cooperative effort with the other agencies involved, the NWS should study the drawdown effect to better quantify this problem.

FINDING 5.13: There were numerous automated stream gage outages throughout the flood, as well as other cases with biased observations, that caused forecasting difficulties. Although backup procedures were often in place, they were not always adequate to meet the needs for a flood of this magnitude.

RECOMMENDATION 5.13: NWS offices should ensure that the backup plans for stream gages in their areas are as complete and thorough as possible. Guidelines should be established and tested to provide a smooth transition to the backup gage when a site's primary gage fails.

FINDING 5.14: Some WSR-88Ds in the flooded area (Chicago, Illinois; Hastings, Nebraska; St. Louis, Missouri; and Topeka, Kansas) experienced extended downtime as a result of lightning strikes and other system failures. The operational availability of the WSR-88Ds must be increased to the 96 percent level specified in the Next Generation Weather Radar (NEXRAD) Technical Requirements to provide the continual time series of rainfall estimates needed for input to flood and flash flood models. Improved methods for lightning protection are being tested using the WSR-88D at Norman, Oklahoma.

RECOMMENDATION 5.14: Lightning protection and other system improvements for the WSR-88Ds required to achieve the contract-specified 96 percent operational availability must be given high priority.

FINDING 5.15: The WSR-88D Principal User Processor does not support digital output or provide sufficient capabilities to make effective, quantitative use of the WSR-88D precipitation estimates. Without the planned AWIPS interactive processing facility and the additional precipitation processing stages planned for AWIPS-era operations, the usefulness of WSR-88D precipitation data for quantitative hydrologic forecast applications is quite limited.

RECOMMENDATION 5.15: The NWS should aggressively pursue installation of AWIPS and AWIPS-type facilities for WSR-88D-equipped offices and for RFCs with significant coverage of their areas of responsibility by WSR-88D systems.

FINDING 5.16: To use the WSR-88D precipitation products as input into the river forecast models, RFC staff had to manually estimate mean areal precipitation (MAP) values using hard-copy printouts. This method is imprecise and time-consuming.

RECOMMENDATION 5.16: Improved computer technology at the RFCs, which is a part of NWS modernization, will help remedy this problem. Every opportunity should be taken to accelerate the implementation of computer processing capabilities at the RFCs. Also, map backgrounds outlining MAP areas should be added to the WSR-88D database.

FINDING 5.17: Graphical representation of satellite-derived isohyetal patterns are not available over the Automation of Field Operations and Services (AFOS) system.

RECOMMENDATION 5.17: The NWS and National Environmental Satellite, Data, and Information Service (NESDIS) should make the Interactive Flash Flood Analyzer (IFFA)-derived precipitation estimates routinely available over AFOS during flash flood events.

FINDING 5.18: The operational use of satellite precipitation estimates has not yet reached its full potential.

RECOMMENDATION 5.18: The NWS and NESDIS should develop a procedure to integrate IFFA-derived rainfall estimates with radar and rain gage observations. The procedure should be flexible enough to compensate for missing observations.

FINDING 5.19: Satellite soil moisture estimates are not currently used in operational river forecasting.

RECOMMENDATION 5.19: NOAA should implement techniques to use remotely sensed (i.e., airborne and satellite) and in situ soil moisture observations in river and flood forecasting.

FINDING 5.20: In at least one case, the hardware configuration of the Automated Local Evaluation in Real-Time (ALERT) system made it technically impossible to transfer NWS river forecasts and warnings to the ALERT system.

RECOMMENDATION 5.20: NOAA Weather Wire is the primary method of NWS product distribution. Nonetheless, NWS forecast offices should ensure that appropriate memoranda of agreement are in place with local parties for appropriate two-way exchange between ALERT systems and the NWS. Where technically feasible, ALERT systems should be modified to facilitate exchange of hydrometeorological data, forecasts, and warnings between ALERT systems and NWS offices. Additionally, local hydrometeorological detection systems, such as ALERT, should be tested periodically to ensure that they are functioning properly.

FINDING 5.21: There was variation in the effectiveness of reporting flood conditions by SKYWARN observers.

RECOMMENDATION 5.21: NWS Headquarters should include in the SKYWARN spotter training syllabus material on flood reporting. Local offices should educate observers about effective flood reporting procedures. Spotters should be encouraged to submit reports when heavy rain and/or flooding occurs (which may require making affordable rain gages available).

FINDING 5.22: Existing stage-discharge relations were exceeded at approximately 100 sites. During the most severe flooding, flow measurements were too sparse.

RECOMMENDATION 5.22: Through collaborative efforts with principal NOAA cooperators, resources (including those to update streamflow measurements and/or perform analyses) need to be made available so that new stage-discharge relations can be developed for these sites.

FINDING 5.23: There were periodic coordination and communications problems associated with data exchange between Federal agencies. For example, appropriate NWS offices did not always receive, in a timely manner, the special streamflow measurements made by the COE or USGS. Additionally, appropriate NWS offices were not always made aware of the streamflow measurement schedules; consequently, it was impossible to infer when NWS offices did not have specific stream discharge measurements. Computer hardware limitations sometimes made it difficult to distribute NWS products to end-users. Consequently, NWS offices were, on occasion, required to fax forecasts and products to end-users.

RECOMMENDATION 5.23: The COE, USGS, and NWS should improve communications links among themselves and with other Federal, state, and local agencies. Specifically, the three agencies should ensure that the data collection schedules and the data distribution mechanisms for stream discharge measurements and other valuable hydrometeorological data sets are well understood and documented. In some cases, computer-to-computer links must be developed and/or upgraded (see Recommendation 6.19).

FINDING 5.24: Precipitation from stranger reports cannot conveniently be input into NWSRFS in its present form. RFC personnel must input these reports at defined nearby missing stations, or manually estimate affected MAP areas. Because of this labor-intensive process, stranger reports provided by WSFOs/WSOs are not usually used.

RECOMMENDATION 5.24: The Office of Hydrology should make the necessary effort to modify the MAP preprocessor so it can accommodate stranger reports.

FINDING 5.25: Much of the early flooding (March, April, and May) in the Upper Midwest was aggravated by above-normal snow cover conditions that developed during the winter and spring of 1993. WSFO Sioux Falls indicated that additional snow water equivalent data would have been valuable before the onset of the 1993 spring snowmelt flooding. The NWS maintains a dense network of airborne flight lines in the Upper Midwest. The airborne snow survey program provides reliable, real-time airborne snow water equivalent measurements over the flight line network for use by NWS field offices when assessing the potential for spring snowmelt flooding.

RECOMMENDATION 5.25: Hydrologists in the regional, RFC, and WSFO offices should request airborne snow surveys over specific areas within their respective regions of responsibility when snow water equivalent is expected to be a major factor associated with spring flooding in the Upper Midwest.

FINDING 5.26: The Great Flood of 1993 left large regions of the Upper Midwest with much above-average soil moisture conditions in the fall of 1993. The existing network of airborne flight lines can be used to make airborne soil moisture measurements in the late fall of 1993. Fall airborne soil moisture measurements are used by NWS hydrologists at the NCRFC when assessing the potential for future flooding during each winter and spring.

RECOMMENDATION 5.26: The Office of Hydrology should make a comprehensive airborne soil moisture survey over the existing flight line network in the Upper Midwest to provide an assessment of soil moisture conditions in the late fall of 1993.

FINDING 5.27: Telephone lines to certain key stream gages were destroyed by the flood.

RECOMMENDATION 5.27: The use of alternative data acquisition systems for stream gage data (e.g., radio, satellite, or meteorburst transmission technology) should be explored to build redundancy into the system at key locations.

FINDING 5.28: The current telecommunications environment for interagency data exchange relies on limited, voice-grade, two-way links. This telecommunications approach did not provide an adequate level of service to the COE and other Federal, state, and private cooperators during The Great Flood of 1993. Moreover, it is completely inadequate to support even higher rates of data exchange. Higher levels of service can be achieved now with available telecommunications technology.

RECOMMENDATION 5.28: The NWS should implement plans for modern telecommunications and information exchange with major water management cooperators and conduct a demonstration of these capabilities as soon as possible.

FINDING 5.29: WSFO Bismarck dials directly into the Environment Canada system for data. There are frequent problems, however, in routing data from the National Center in Toronto through the NMC to the WSFO. These data are often delayed or unavailable.

RECOMMENDATION 5.29: NWS and Environment Canada field offices should continue their good working relations. The NMC and Environment Canada's National Center should investigate the possibility of improving the interface between their computer systems.

FINDING 5.30: There is no backup should there be a disastrous failure of the NOAA Central Computer Facility (NCCF) for those RFCs that are still dependent on the facility.

RECOMMENDATION 5.30: As quickly as possible, NOAA should develop disaster contingency plans to use distributed AWIPS-type RFC systems to provide backup for NCCF-dependent RFCs until AWIPS is deployed.

FINDING 5.31: Despite the limited capabilities of AFOS and the fact that those capabilities were pushed to their limits throughout the flood event, AFOS generally performed in a reliable and stable manner. Concern was expressed that AFOS, which has exceeded its original life expectancy, will not be able to continue reliable performance.

RECOMMENDATION 5.31: AFOS must be maintained as a highly reliable operational NWS system until replaced by AWIPS at the earliest possible date.

FINDING 5.32: Communications between RFCs and the NCCF are critical to RFC operations and are a weak link in the current river forecast system.

RECOMMENDATION 5.32: The NWS must evaluate its backup procedures to ensure there is sufficient communications capacity to support operations during major flooding.

FINDING 5.33: Current RFC communications capabilities are too slow for extreme loads generated at times of widespread major flooding. During The Great Flood of 1993, a workaround was developed to operate both the dedicated 9600-baud circuit simultaneously with the 4800-baud dial backup circuit for the North Central RFC. This was effective in increasing the communications capacity by 50 percent, but it is expensive and has no backup.

RECOMMENDATION 5.33: All RFCs should be made aware of the potential use of the dial backup remote job entry circuit as an emergency, temporary boost to their NCCF telecommunication capabilities.

FINDING 5.34: Some offices lack large workspace areas for use of bulky items such as topographic maps.

RECOMMENDATION 5.34: The layout of new facilities being built as part of modernization and associated restructuring (MAR) should be configured to consider the requirement for flat workspace. Where practical, current offices should be rearranged to accommodate this requirement.

FINDING 5.35: The posting, data management, and quality control of hydrometeorological data, in general, is too slow, laborious, nonsystematic, and incomplete.

RECOMMENDATION 5.35: The AWIPS system (which will employ sophisticated graphics, database, and computing capabilities that far exceed those currently in use) should eliminate system reliability problems and facilitate data management tasks. It is essential that AWIPS be implemented as soon as possible.

FINDING 5.36: Users indicated a need for more frequent river forecast updates. The RFC model update cycle is dependent on batch computer operations over a communications link to the NCCF. This problem was less acute for the MBRFC because some forecast operations are run locally on a minicomputer. Batch-mode operations not only contribute to delays in forecast updates but also inhibit the forecaster from gaining the level of insight into hydrometeorological conditions that is possible with local, interactive processing. This contributed to delays in forecast release times.

RECOMMENDATION 5.36: The NWS should move as quickly as possible to install on-site, interactive forecast systems in RFCs to speed up production of forecast products, including updated river forecasts and contingency forecasts based on various precipitation scenarios. Although the AWIPS system will ultimately support this interactive RFC environment completely (see Recommendation 5.35), opportunities to take advantage of AWIPS-type facilities and/or early AWIPS platforms must be maximized. Additionally, Hydrologic Service Area (HSA) offices should work with the RFCs to coordinate event-driven updates that provide users with timely flood warning information.

FINDING 5.37: Various system hardware problems and the lack of technician support required hydrologists to perform electronic maintenance functions to keep systems operating.

RECOMMENDATION 5.37: Contingency plans should be developed by the Office of Systems Operations and the NWS regions to ensure that all RFCs have adequate electronic systems support during critical flood events.

9.6 WARNING AND FORECAST SERVICES (CHAPTER 6)

FINDING 6.1: Long-term river forecasts significantly underestimated stages because they did not include estimates of future precipitation.

RECOMMENDATION 6.1: Information contained in precipitation forecasts and outlooks must be factored into river forecasts.

FINDING 6.2: Current precipitation forecasts are not available in a format that allows easy incorporation into operational river forecast procedures.

RECOMMENDATION 6.2: Manually prepared precipitation forecasts and outlooks must be formatted to allow for the efficient, automated incorporation of digital precipitation forecasts into river forecast procedures.

FINDING 6.3: Precipitation forecasts are least accurate at the smaller scales required by current hydrologic forecast procedures. Nevertheless, QPF information at current skill levels contains valuable information that could benefit hydrologic modeling.

RECOMMENDATION 6.3: The NWS must focus efforts to: (1) enhance precipitation forecasting on the space and time scales needed in hydrologic models and (2) develop methodology that incorporates QPF information into advanced hydrologic modeling approaches.

FINDING 6.4: Extended streamflow prediction techniques provide a promising framework to incorporate precipitation forecasts into the hydrologic modeling and forecast system.

RECOMMENDATION 6.4: The NWS should support research, development, and operational testing to incorporate current QPF and other precipitation outlooks into river forecasting procedures.

FINDING 6.5: Effective integration of QPF information into hydrologic models is extremely difficult and will require close collaboration between NMC and the RFCs.

RECOMMENDATION 6.5: An exchange program should be instituted whereby RFC staff visit NMC and NMC staff visit various RFCs to address the technical and scientific problems preventing effective use of QPF in operational river forecast models.

FINDING 6.6: WSFOs and WSOs exhibited a wide range of philosophies in the issuance of warnings versus statements. The decision of what type of product to issue can become a judgment call. To some degree, it is based on the geographical area and associated flood climatology.

RECOMMENDATION 6.6: All offices should review Weather Service Operations Manual chapters that describe types and content of products and adhere to these guidelines as closely as possible. The Regional Hydrologist should coordinate with the SHs to ensure consistent use of products (see Recommendation 6.17).

FINDING 6.7: No systematic, national program exists to verify river forecasts.

RECOMMENDATION 6.7: The West Gulf RFC, other participating field focal points, and the Office of Hydrology have designed an appropriate national verification system. These offices should continue development and implementation of the procedures and software required for the system.

FINDING 6.8: A growing recreational area along the Missouri River south of Sioux Falls often draws as many as 100,000 campers. There is no way to provide weather information to these campers.

RECOMMENDATION 6.8: The NWS should provide a NOAA Weather Radio (NWR) repeater in or near the recreational area.

FINDING 6.9: WSFOs and RFCs were inadequately staffed to manage a disaster of this magnitude. In the few locations where extra personnel were imported from NWS offices that were not currently experiencing severe hydrologic problems, impacts were always positive.

RECOMMENDATION 6.9: Each region should establish a personnel backup procedure for large, protracted events.

FINDING 6.10: WSO Columbia staff was required to provide radar backup when the WSFO St. Louis' WSR-57 Network Radar was down. This created an additional burden on the already overworked staff. This problem will be slowly resolved when WSR-88D radars begin to be commissioned.

RECOMMENDATION 6.10: Every effort should be made to reach acceptable operational availability levels for commissioning WSR-88D radars as soon as possible.

FINDING 6.11: Many meteorological forecasters did not feel proficient handling prolonged and major hydrologic operations when an SH was not in the office or on staff. WSFO Topeka has no SH. Consequently, it was much more difficult to maintain a high-quality hydrologic program without immediate access to specialized hydrologic expertise. Those offices with SH positions reported them indispensable in the capacity of local expert who coordinates hydrologic training of office staff, data flow, user interaction, media contacts, and forecast services.

RECOMMENDATION 6.11: In the modernized weather service, the NWS should revisit its planned staffing allocations for SHs necessary to support those WFOs that have high levels of significant hydrologic activity.

FINDING 6.12: The SHs served as the primary contacts at the WSFOs to accumulate a wide variety of data from a large number of hydrometeorological data networks supported by numerous Federal, state, and local agencies. The SHs were creative and innovative in their efforts to ensure that critical hydrometeorological data were available for use in the NWS hydrologic forecast and warning program.

RECOMMENDATION 6.12: See Recommendation 6.11.

FINDING 6.13: Both MBRFC and NCRFC provided extended coverage for most of the protracted flood event on a 7-days-a-week schedule well into the evening (usually until 10 or 11 p.m.). Nevertheless, certain users cited an inability to acquire needed information during hours when the RFCs were not in operation, and many end-users require 24-hour RFC support during major flood events. The NCRFC provided around-the-clock coverage for 4 days during the event. The MBRFC provided 24-hour coverage for 2 days.

RECOMMENDATION 6.13: RFCs should be staffed for 24-hour coverage during major flood events.

FINDING 6.14: By the time some RFC forecasts were received by the WSFOs, observed river stages exceeded forecast stages. As the modernization process improves the timeliness of the forecast cycle, improves the forecast accuracy, and reduces product transmission delays, the frequency of this type of occurrence will be reduced.

RECOMMENDATION 6.14: Whenever RFC forecasts are obviously in error, WSFO forecasters should immediately coordinate with the supporting RFC before issuing any public product based on these forecasts.

FINDING 6.15: The NCRFC staff stated that if the planned staffing for Hydrometeorological Analysis and Support forecasters in the modernized weather service had been on board, the NCRFC would have been able to analyze, in greater depth, the radar rainfall estimates and QPF products.

RECOMMENDATION 6.15: Within the current budget constraints, NWS Headquarters and regional offices should do everything possible to complete the modernized staffing levels for the RFCs.

FINDING 6.16:: There were end-users that did not have access to and/or the expertise required to interpret the voluminous amounts of information contained in the large number of NWS products. This potentially can become an even greater problem in the modernized NWS when much more site-specific information becomes available.

RECOMMENDATION 6.16: It is critical that the packaging and distillation of the relevant information for water control and emergency management decision makers be improved. Some of this problem may subside as the NWS moves into modernized methods of providing information in graphical format. Until then, HSA offices and RFCs should contact their principal governmental users to discuss and implement innovative packaging of information tailored to their local areas and needs.

FINDING 6.17: During the flood event, a large number of flood products were issued including Flood Warnings, Flash Flood Warnings, and Urban and Small Stream Flood Advisories. The appropriate choice of product headers, and when to use them, at times confused NWS meteorological forecasters.

RECOMMENDATION 6.17: The SHs should ensure that all office staffs are trained on the appropriate use of product types.

FINDING 6.18: Extra NWS personnel rotated into the RFCs and WSFOs and worked many hours of overtime. The scheduling and rescheduling of leave or training for WSFO and RFC staff became a factor in maintaining adequate staffing levels.

RECOMMENDATION 6.18: During long, widespread record events of this type, essential personnel should return to their duty stations from long-term training assignments. Anyone withdrawn from long-term training under these conditions should be rescheduled for a later date.

FINDING 6.19: There are three different RFCs that provide forecasts to the St. Louis COE covering the upper Mississippi River basin (NCRFC), the Missouri River basin (MBRFC), and the lower Mississippi River basin (LMRFC). The St. Louis COE District Office expressed concern that the forecasts from the three NWS offices were not always internally consistent.

RECOMMENDATION 6.19: The COE and NWS should establish a technical working group consisting of personnel from all appropriate NWS and COE offices to ensure that techniques and procedures are fully understood and that clear points of contact are established to clarify any potential misunderstandings during flood events. Moreover, the NWS and COE offices should implement a personnel exchange program whereby personnel from the two agencies would work on-site in the other cooperating agency's office either part-time or full-time.

FINDING 6.20: An inability to determine accurately the amount and time distribution of precipitation led to uncertainty in forecasting both volume and timing of flood crests. As specifically noted in the Des Moines, Iowa, case study, inaccurate precipitation estimates are generally considered to be the greatest single source of river forecast error. The NWS plans to produce precipitation estimates which combine rain gage observations, WSR-88D precipitation estimates, and satellite observations in sophisticated, multistage, multisensor precipitation estimates using both interactive and automated quality-control features. These plans require the completion of the WSR-88D radar network and the on-site, interactive processing provided by AWIPS.

RECOMMENDATION 6.20: Completion of the WSR-88D network and the AWIPS program must continue to have high priority (see also Recommendations 5.14 and 5.15).

FINDING 6.21: Record flows occurred earlier than were forecast at many points along the Des Moines River and its tributaries due, in part, to routing procedures that overestimated travel times. Current routing procedures are based on observed hydrograph data from previous floods.

RECOMMENDATION 6.21: Empirical routing procedures should be recalibrated to account for maximum discharges that occurred during The Great Flood of 1993.

9.7 COORDINATION AND DISSEMINATION (CHAPTER 7)

FINDING 7.1: The special teleconferences involving RFCs, WSFOs, NMC, and the Office of Hydrology during the 1993 flood event were beneficial in several aspects, especially to RFCs that were trying to consider future hydrometeorological conditions over their broad areas. Certain improvements, however, in the management and content of the teleconferences would have made them even more beneficial.

RECOMMENDATION 7.1: The logistics of handling and guidelines for the content of the teleconferences should be more streamlined by regional, NMC, Office of Meteorology, and Office of Hydrology personnel. The information on QPF products conveyed from NMC should have concentrated on additional physical insights into the forecasts, and their potential accuracies, beyond that contained in the issued products.

FINDING 7.2: NWS teleconferences did not use video.

RECOMMENDATION 7.2: The NWS should investigate the feasibility and evaluate the potential effectiveness of video teleconferencing during protracted events such as The Great Flood of 1993.

FINDING 7.3: In some cases, differences in RFC formats used to transmit river forecasts required editing by WSFOs and WSOs prior to issuance to the public.

RECOMMENDATION 7.3: All RFCs should use the same format in transmitting river forecasts and other products.

FINDING 7.4: Several internal NWS products, such as the State Forecast Discussion and Excessive Rainfall Discussion, were widely distributed to the media. In some instances, these technical products were taken out of context, sensationalized, and presented as official NWS forecasts by the media.

RECOMMENDATION 7.4: NWS Headquarters should complete a review of the policy on dissemination of internal forecast discussion products through the NOAA Family of Services.

FINDING 7.5: In some communities there appeared to be a lack of communication and coordination among different agencies within the same community and officials of adjoining communities. Critical river and flood forecast information needed to prevent damage to major facilities was sometimes unavailable to all agencies.

RECOMMENDATION 7.5: National, regional, and local NWS offices should team with Federal, state, and local agencies to coordinate more frequent communication to ensure that needed information is distributed among all agencies.

FINDING 7.6: County officials often failed to call the NWS when levees failed. In many cases, the media knew about failures before the NWS. For example, St. Louis emergency response teams, such as the Red Cross and Disaster Services, reported that some local officials were slow to report levee breaks to the local NWS office, which resulted in delays in the issuance of flash flood warnings by the NWS.

RECOMMENDATION 7.6: More intensive efforts should be undertaken at national, regional, and local levels to ensure maximum coordination and cooperation among agencies involved in disaster mitigation. While MAR expansion of local staffs to include a Warning Coordination Meteorologist at each WFO should promote better coordination, immediate efforts are needed.

FINDING 7.7: Emergency operations centers (EOC) were established at several locations including Kansas City, Minneapolis, Des Moines, and St. Louis. These centers were staffed by key personnel from a variety of Federal, state, and local agencies involved in coordinating flood operations and disseminating information. WSFO Des Moines and the North Central RFC\WSFO Minneapolis maintained a periodic presence at EOCs through much of the flood event. Given the limited staffing available, it is out of the question for any NWS office to provide around-the-clock, on-site staffing support for EOCs. Although other WSFOs and RFCs provided information, they did not provide on-site representation at EOCs. In other cases where official EOCs were not established, close alliances were formed with the COE, the USGS, and local officials, such as in North Dakota.

RECOMMENDATION 7.7: All WSFOs, RFCs, and WSOs should provide the highest level of support possible to EOC operations within their service areas during emergency situations. Highly reliable communications between the EOC and the WSFO/WSO/RFC is essential. When feasible, periodic, on-site EOC support should be provided. Such actions would improve coordination and cooperation in addition to increasing NWS visibility.

FINDING 7.8: The COE district offices generally provided reservoir outflow data on a periodic basis to the RFCs and to some WSFOs; however, the COE offices expressed concern over problems and inefficiencies in the connections and transfer rates experienced with antiquated NWS computers and communication equipment. The NWS, in some cases, had to fax products to the COE.

RECOMMENDATION 7.8: Over the short term, the NWS and COE should take all feasible actions to improve communications systems and data exchange procedures. Over the longer term, the NWS and COE should ensure that their respective RFC and water control district gateway systems are optimally interfaced.

FINDING 7.9: The Rock Island COE District strongly encouraged cross-training between COE and RFC personnel. Cross-training of NWS and COE personnel would substantially improve intra-agency and interagency operations, not only during flood events when personnel may be shifted from one office to another but also during routine operations.

RECOMMENDATION 7.9: See Recommendation 6.19.

FINDING 7.10: More timely and effective ways are needed for computer-to-computer exchange and dissemination of data and products, including graphic displays, between NWS field offices and their cooperators and end-users.

RECOMMENDATION 7.10: The NWS should actively pursue the multiple avenues required to provide timely products and information in appropriate formats to the various communities of end-users (see Recommendation 7.8). As part of this effort, NOAA/NWS should improve various aspects of its product dissemination policies.

FINDING 7.11: Certain cooperating agencies, especially the COE, noted frequent difficulty in accessing RFCs and WSFOs through commercial telephone lines.

RECOMMENDATION 7.11: The NWS should install additional, private telephone lines as required, if not on a permanent basis, then at least on a temporary basis during severe weather and flood events of this magnitude. The additional lines will help critical cooperators coordinate with NWS offices.

FINDING 7.12: Arrangements to handle NMC Meteorological Operations Division interactions with the Federal Emergency Management Agency (FEMA) were accomplished largely on an ad hoc basis in response to the emergency situation.

RECOMMENDATION 7.12: NMC should establish a better level of understanding with other Federal agencies concerning what information can be provided on an emergency basis, how it should be provided, and who are the appropriate contact points.

FINDING 7.13: The National Flood Insurance Program, administered by the FEMA through the Community Rating System, encourages coordination among various local and regional agencies in the development of flood warning plans. Communities that qualify for participation in the Community Rating System receive discounts on flood insurance policy premiums throughout the community.

RECOMMENDATION 7.13: The NWS should encourage FEMA and the National Flood Insurance Program to strengthen recognition of community flood warning activities and to expand eligible activities to include comprehensive flood action plans. These flood action plans are designed to mitigate the impact of impending flooding, such as the identification of flood magnitude thresholds that trigger action (e.g., sandbagging) to protect critical facilities and infrastructure.

FINDING 7.14: The magnitude of The Great Flood of 1993 made the central United States the focus of national and worldwide attention, which led to intense media interest. The volume of telephone media queries for critical and noncritical flood information overtaxed NWS staff at national, regional, and local levels. All offices in the affected areas were inundated with requests to provide interviews, material, and information to the media and NWS Headquarters for input to congressional briefings and for other program exercises.

RECOMMENDATION 7.14: Because of the long duration of The Great Flood of 1993, additional resources to help handle public affairs functions should have been available. A plan for activation of additional public affairs personnel support for such events should be developed. Additional training on procedures for interaction with the media and other external parties should be provided for some offices.

FINDING 7.15: Some media members suggested that better coordination of the NWS product release times to coincide with the broadcast schedules would have allowed for more timely and effective broadcast of NWS products to the public.

RECOMMENDATION 7.15: The NWS should continue all possible acceleration of MAR components including lengthened standard hours of operation, staff augmentation, and implementation of new technologies at RFCs, which should allow initial morning river forecasts to be issued in the 7 a.m. time frame.

FINDING 7.16: In many instances, local communities and municipalities are not making effective use of the NOAA Weather Wire Service (NWWS). In some cases, agencies were not even aware of the existence of the NWWS. Many communities did not use NWWS because of: (a) the high cost of the service, (b) the need for tailored forecast information, and (c) the high volume of products disseminated.

RECOMMENDATION 7.16: The NOAA/NWS should explore the possibility of lowering NWWS costs, study the ramifications of not lowering NWWS costs, and redouble efforts to make other agencies aware of NWWS availability and features. Additional sources of product distribution, such as Internet, should be explored. Also, NOAA should encourage FEMA to provide support and assistance to communities so they can subscribe to the NWWS.

FINDING 7.17: Most of the public is unaware of the availability of NWR, even though it broadcasts across most of the United States.

RECOMMENDATION 7.17: The NOAA/NWS must make a substantially greater effort to educate the public on the availability of NWR and of the life-saving service it provides.

FINDING 7.18: Broadcasts of flood forecasts on NWR were sometimes not up to date. Some river products did not specify the time of the observed stage. It is especially critical during epic weather and flood events, such as The Great Flood of 1993, that personnel at NWS offices take extra steps to ensure that information broadcast on NWR is updated frequently so that NWR listeners receive only the latest information.

RECOMMENDATION 7.18: The current NWR policy of broadcasting the time and date for specific observations should be adhered to. See Finding and Recommendation 5.36 pertaining to more frequent forecasts and updates.

FINDING 7.19: Weather radar imagery and graphic products were not available to most Federal, state, and local agencies.

RECOMMENDATION 7.19: The NWS should determine whether current and planned provisions for dissemination of weather radar products are adequate to meet the needs of NOAA cooperators throughout the Nation.

FINDING 7.20: Some county Emergency Management Agencies (EMA) stated that the cost of becoming a NEXRAD Information Dissemination System (NIDS) subscriber exceeds financial resources of many county EMA offices, especially in counties with small populations.

RECOMMENDATION 7.20: The Federal Government should ensure that the NIDS providers continue to offer lower cost capability for these counties. The local WSFOs should also continue emergency coordination with county EMAs.

9.8 PREPAREDNESS AND USER RESPONSE (CHAPTER 8)

FINDING 8.1: Some basin and topographic maps at WSOs were outdated or missing.

RECOMMENDATION 8.1: Offices in need of topographic maps should procure them directly from the USGS. NWS Headquarters and regional offices should establish procedures to generate and update WSFO basin maps.

FINDING 8.2: County emergency management officials expressed general satisfaction with NWS services. They sometimes noted a difference between statements issued by the COE and the NWS. Often, since the COE had a physical presence at the flood site, local authorities used information provided by the COE.

RECOMMENDATION 8.2: The NWS should improve coordination with county and state EMAs and EOCs through periodic review of action plans, participation in mock disaster exercises, and other planning approaches. Improved real-time coordination between the NWS and EOCs is addressed in Recommendation 7.7.

FINDING 8.3: Most public works and emergency management departments in major municipalities have flood operation manuals. These manuals contain information on critical decision points for which various actions are initiated once critical river stages are reached (or forecast). These manuals were not always available in some NWS field offices.

RECOMMENDATION 8.3: The NWS should obtain the flood operation manuals, as well as maintain and improve relationships with respective public works agencies and EMAs. Relevant information from these manuals should be incorporated in the Service Hydrologist Information Management System.

FINDING 8.4: St. Charles County, Missouri, which has a moderate population, maintains a modern EOC operating a state-of-the-art Emergency Information System. Private sector funding helped to build an advanced EOC that uses NWS warnings and forecasts to better serve the public.

RECOMMENDATION 8.4: Federal, state, and local agencies are encouraged to coordinate and to expand this type of modernized emergency system nationwide. This would improve dissemination and increase efficiency of providing NWS information to the public.

FINDING 8.5: The media and the public do not fully understand hydrologic terminology, procedures, and forecast products.

RECOMMENDATION 8.5: The NWS and NOAA Public Affairs, at all levels, should develop a public education program to increase awareness of and understanding about the hydrology program by using brochures, news releases, fact sheets, and other background materials, along with increased interaction with the media.

APPENDIX A

DISASTER SURVEY TEAM CONTACTS

A.1 NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION/ NATIONAL WEATHER SERVICE

Regional Hydrologist, Central Region
- Lee Larson, Regional Hydrologist

North Central RFC Minneapolis, Minnesota
- Dean Braatz, Hydrologist in Charge
- Pat Neuman, Hydrologist

Missouri Basin RFC Pleasant Hill, Missouri
- Larry Black, Hydrologist in Charge
- Jack Vochatzer, Senior Hydrologist
- Julie Meyer, Senior Hydrologist
- John Pescatore, Hydrologist

WSFO Bismarck, North Dakota
- Donald Stoltz, Area Manager
- Charlene Prindiville, Service Hydrologist

WSFO Chicago, Illinois
- Bob Somrek, Deputy Meteorologist in Charge
- Jim Allsopp, Warning Coordination Meteorologist
- William Morris, Service Hydrologist

WSFO Des Moines, Iowa
- John Feldt, Meteorologist in Charge
- Lee Anderson, Deputy Meteorologist in Charge
- Larry Ellis, Service Hydrologist

WSFO Milwaukee, Wisconsin
- Ken Rizzo, Area Manager
- Tony Siebers, Deputy Meteorologist in Charge
- Brian Hahn, Service Hydrologist

WSFO Minneapolis, Minnesota
- Craig Edwards, Area Manager
- Glenn Lussky, Deputy Meteorologist in Charge
- Gary McDevitt, Service Hydrologist
- Byron Paulson, Lead Forecaster
- Sam Stanfield, Meteorological Technician

WSFO Omaha, Nebraska
- David Wert, Deputy Meteorologist in Charge
- Roy Osugi, Service Hydrologist

WSFO St. Louis, Missouri
- Steve Thomas, Area Manager
- Ted Schroeder, Lead Forecaster
- Jack Burns, Service Hydrologist
- Jim Kramper, Warning Coordination Meteorologist

WSFO Sioux Falls, South Dakota
- Greg Harmon, Area Manager
- Cliff Millsapps, Service Hydrologist

WSFO Topeka, Kansas
- Curt Holderbach, Area Manager
- Don Rogers, Deputy Meteorologist in Charge
- Steve Kruckenberg, Service Hydrologist - Goodland, Kansas
- Mike Akulow, Warning Coordination Meteorologist
- Ken Labas, Science and Operations Officer

WSO Columbia, Missouri
- David Larm, Official in Charge
- Roger Pratt, Electronics Technician

WSO Fargo, North Dakota
- Lou Bennett, Official in Charge

WSO Kansas City, Missouri
- Randall McKee, Meteorologist in Charge
- Steve Predmore, Service Hydrologist
- Bill Bunting, Warning Coordination Meteorologist
- Steve Runnels, Meteorologist

A.2 U.S. ARMY CORPS OF ENGINEERS

Kansas City District
- Jerry Buehre, Chief, Water Control Section

Lower Mississippi River Division (phone contact)
- Joe McCormick, Assistant Chief of Operations

Office of Chief Engineer, Washington, D.C. (phone contacts)
- Earl Eiker, Chief of Hydrology
- Charles Sullivan, Chief of Water Control and Water Quality

Omaha District
- Phyllis Pistillo, National Emergency Manager
- Wayne Dorough, Chief, Hydraulic Engineering Branch
- Kevin Grode, Hydraulic Engineer
- Kathy Willcuts, Chief, Water Control Section

Omaha Division
- Chet Worm, Chief, Reservoir Regulation Section
- John Countee, National Emergency Program Manager

Rock Island District
- William Koellner, Chief, Hydraulics Branch

St. Louis District
- Bill Arthur, Asst. Chief, Hydrologic and Hydraulics Branch
- Gary Dyhouse, Chief, Hydrologic Engineering Section
- (phone contacts):
- Tom Lovelace, Chief, Hydrologic and Hydraulics Branch
- Don Coleman, Potamology Section

St. Paul District
- Ed Eaton, Chief, Water Control Branch
- Bob Engelstad, Chief, Hydraulic Engineering
- Major Andy Reese, U.S. Army
- Pat Foley, Chief, Hydrology Branch
- David Christenson, Chief, Emergency Management

Saylorville Reservoir and Dam, Johnson City, Iowa
- John Demarce, Manager (phone contact)

A.3 EMERGENCY MANAGEMENT AGENCIES

Chicago FEMA (phone contact)
- Stuart Rifkind, Chief, Emergency Management Division

Columbia/Boone County EMA
- Michael Sanford, Director

Iowa Emergency Management Division
- Ellen M. Gordon, Administrator

Kansas City Emergency Operations Center
- Joseph Henry Munoz, Chief

Lincoln County (Missouri) Emergency Management Agency
- Dennis Harrel, Emergency Management Coordinator

Minnesota State Emergency Management Agency
- Jim Franklin, Director
- Judy Rue, Natural Disaster Coordinator
- Brad Wise, Duty Officer of Supervision

Missouri State Emergency Management Agency
- Charles Walker, Director

St. Charles County Emergency Management Agency
- Gary Schuchardt, Director
- Rod Zaire, Communications Officer

St. Louis County Police Emergency Management Office
- Michael Redman, Communications Coordinator

Sioux Falls Emergency Management Agency
Tom Welch, Region 8 Coordinator
Scott County (Iowa) Emergency Mgmt. Agency (phone contact)
Ross Bergen, Disaster Services, Operations Officer

A.4 NEWS MEDIA

Columbia
KOMU TV
Ron Taylor, News Director
Des Moines
WHO Radio
Jodi Chapman, Weather Reporter
KCCI TV
Dave Busik, News Director
Gary Ambel, Meteorologist
Des Moines Register
John Carlson, Reporter
Kansas City
KMBC TV
Brian Bracco, News Director
Brian Busby, Chief Meteorologist
Minneapolis
KARE TV
Paul Douglas, Chief Meteorologist
WCCO TV
Mike Fairbourne, Chief Meteorologist
Rebecca Kolls, Meteorologist
St. Louis
KMOX Radio
Thomas Langmeyer, Program Director
John Angelides, News Director
St. Louis Post Dispatch
Laslo Domjan, City Editor
Bill Allen, Science Writer
Tim O'Neil, Reporter
Virgil Tipton, Reporter
Associated Press
Lori Rose, Assignment Editor
KMOV TV
Trish Brown, Chief Meteorologist

KSDK TV
    Scott Connell, Meteorologist
    John Fuller, Meteorologist

A.5 OTHERS

Iowa

Davenport Public Works (phone contact)
    Dee Breummer, Public Relations Officer
Des Moines City Manager's Office
    Cy Carney, City Administrator
Des Moines Public Works
    Patrick Kozitza, Assistant Director
    Darwin Larson, Senior Engineer
Des Moines Water Works
    L.D. McMullin, General Manager
    Marty Lausiti, General Services Director
Iowa American Water Company (phone contact)
    Dave Hansen, Risk Management Officer
West Des Moines City Manager's Office
    Art Pizzano, City Manager
    Randy Bracken, Fire Chief
    Edward Stangl, Environmental Engineer

Missouri

American Red Cross, St. Louis
    Andrea Beer, Disaster Specialist
    Michael Monehan, Disaster Specialist
    Michael Miller, Dispatcher
    Jim Udell, Disaster Coordinator
American Waterways Operators, Washington, D.C.
    Jennifer Boucher, Public Affairs Officer (phone contact)
Coast Guard/Army Corps Command Center, St. Louis
    Jon Burk, Chief Planner, USCG
    LT Jim Curry, USCGR
Congressman Jim Talent's Office
    Brian Borsa, Staffer
Federal Aviation Administration
    Jim Adelman, Airway Facilities Specialist
Jersey County (Illinois) Sheriff's Office
    Frank Yocom, Sheriff

Kansas City Public Affairs Office
    George Hanley, Public Affairs Officer
Lincoln County (Missouri) Sheriff's Office
    Everett Rottger, Sheriff
Missouri Department of Transportation
    Gene Stephens, Track Safety Specialist
Missouri Highway and Transportation
    Jack Hynes, Director of Transportation
    Mel Sundermeyer, Administrator of Waterways and Railroads
St. Charles County Farm Bureau
    Earl Heitmann, President
Waterways Journal, St. Louis
    Dan Owen, Associate Editor

Virginia

American Commercial Barge Line, CSX Corp
    Vance Richardson, Manager, Editorial Services

APPENDIX B

PRECIPITATION FORECASTING

B.1 INTRODUCTION

A key input to any river forecast model is precipitation. Current operational river forecast procedures generally start with observed precipitation and predict its movement through the "earth portion" of the hydrologic cycle. The current procedures provide valuable forecast information for downstream locations on major river systems, where the time between rainfall and river rise is days to weeks.

Forecasts for periods beyond the time between rainfall and river rise at a particular location depend on the ability to quantitatively predict future rainfall. As indicated in Section 4.3.1.1, river forecasts are based on the integration of computations for relatively small subbasins. Therefore, in addition to predicting the time and amount of precipitation, the location of the rainfall also needs to be precisely specified so that it is geo-referenced to the correct subbasin. Even for larger river systems, unless the timing, magnitude, and location of the predicted rainfall can be accurately delineated, errors in the timing and magnitude of downstream crest forecasts can be substantial.

One of the frequent questions encountered by the disaster survey team had to do with the general absence of use of quantitative precipitation forecasts (QPF) in the hydrologic forecasts issued throughout this event. This appendix discusses some of the more significant issues raised by this question. Section B.2 examines QPFs produced by the National Weather Service's (NWS) National Meteorological Center (NMC) in some detail, including an assessment of the skill level. The section also includes three case studies of events that generated significant flood-producing precipitation during The Great Flood of 1993. This is followed by a limited evaluation of the QPFs viewed in terms of input quantities needed by current river forecast models (Section B.3). Section B.4 addresses the possible use of precipitation forecasts and outlooks with Extended Streamflow Prediction (ESP) modeling techniques to produce probabilistic river forecasts. The appendix concludes with an assessment of current capabilities and suggestions to enhance river forecast schemes (Section B.5).

B.1.1 TYPES OF PRECIPITATION FORECASTS

On a daily basis, NMC produces a set of maps specifying the spatial distribution of the magnitude of precipitation expected (QPFs) throughout the United States. The forecasts are for 6- and 24-hour periods. In addition to the Day 1 QPF, a Day 2 forecast for the same time period is issued 24 hours before the beginning of the valid period; and the Day 2 is revised each afternoon after receipt of the 12:00 Universal Coordinated Time[1] (UTC) model guidance packages. On the same set of maps, areas forecast to have excessive rainfall are also indicated. In addition to maps showing the spatial distribution of the forecast precipitation, text products are prepared discussing the meteorological reasoning that went into the QPFs. While excessive rainfall discussions are regularly issued twice a day, updates are prepared when heavy rainfall conditions change rapidly.

NMC also issues 3- to 5-day precipitation anomaly forecasts every day. These are categorical forecasts with regions being assigned to an above-normal, normal, or below-normal chance of occurrence. On a daily basis, 5-day total precipitation categorical forecasts are also prepared. The categories are: (1) no precipitation, (2) light, (3) moderate, and (4) heavy precipitation. Three times a week, 6- to 10-day precipitation forecasts are issued using the same four categories as for the 5-day precipitation forecasts. These forecasts are mainly determined by statistical climatology. Finally, twice a month, NMC issues 30-day precipitation outlooks and on a monthly basis 90-day precipitation outlooks. The outlooks indicate the probabilities of precipitation amounts deviating from the climatological norm. Although this appendix focuses primarily on the use of short-term, 24-hour, Day 1 QPF, it includes perspectives on how precipitation forecasts/outlooks for longer lead-times may be included in future hydrologic forecast procedures.

B.2 QUANTITATIVE PRECIPITATION FORECASTING

Due to the many variables that enter into the forecast picture each day, forecasts for the precise location and amount of convective rainfall is among the most difficult of the many weather forecast problems, especially when a forecaster is asked to specify the temporal and spatial details many hours before the event begins. It has been documented that the majority of summer mesoscale convective rainfall events occur at night. Thus, 24-hour QPFs are issued from NMC about 12-18 hours in advance of the rain event ("Day 1 forecast"). The forecaster relies quite heavily on model circulation forecasts and interpretation of current data, including satellite and radar imagery, and attempts to blend all of the available information into a logical and accurate forecast.

From NMC's viewpoint, there has not been a warm season[2] with a circulation pattern similar to that which prevailed during June and July of 1993 since QPFs were first issued in 1960. The

---

[1] UTC is also known as Greenwich Mean Time. In the Midwest, it is shifted from local daylight time by 5 hours. Thus 12:00 UTC is the same as 7 a.m. CDT.

[2] The meteorological processes influencing precipitation differ significantly throughout the year. Winter precipitation is due mainly to frontal cyclones, while summer rainfall is predominantly produced by convection. The ability to model winter precipitation is better than the skill in predicting summer rainfall. Since both the physical processes leading to precipitation and the forecast skill are different, analysis and verification of QPF is partitioned between a cool season (October-March) and a warm season (April-September).

striking feature of the 850-mb mean wind vector during mid-June to late July 1993 (Figure 3-8(a)) is the strength of the southerly low-level wind field across the western Gulf of Mexico and south-central United States. Also quite evident is the west to northwest wind over the Upper Midwest and northern Rockies. These features combined to create a massive low-level convergence zone across the central United States. Figure 3-8(a) shows that a large supply of very warm, moist, and unstable air was being rapidly transported into a waiting low-level convergence zone.

Figure 3-7(a) shows the mean 250-mb level wind vectors and mean wind speed for the same period. This figure shows that an upper-level jet pattern persisted during this critical 6-week period and provided extremely strong upper-level dynamics favorable to sustaining convective activity. Even in 6-week mean charts, the coupled low-level and high-level jet structure is very evident, with the central United States under the influence of the right entrance region (i.e., right rear quadrant) of the 250-mb jet, while simultaneously being located in the left exit region (i.e., left forward quadrant) of the low-level jet. The importance of this structure was found in individual precipitation situations where the coupled jets acted to produce very large precipitation events. Although the concepts of the coupled jets were empirically used by NMC forecasters for many years, recent documentation[3] has served to focus increased attention on situations featuring coupled low-level and high-level jets.

Since the prevailing low-level wind field over the south-central United States is southerly during the summer, it is useful to note how the 1993 summer wind field compared to a normal situation. Figure 3-8(b) shows the anomalous low-level wind vectors and analyzed wind speed. The low-level mean southerly wind exceeded by 4 m/s the mean wind for the 1979-1988 base period. Figure 3-7(b) shows the 250-mb anomalous wind vector field for the same period. On this chart, the 250-mb winds exceeded the reference 10-year average by over 10 m/s. Summarizing the impact of this flow regime, an extremely impressive synoptic situation prevailed for a 6-week period. This synoptic pattern ensured that the major ingredients for mesoscale convective rainfall and attendant flooding would occur and be sustained over a multistate area in the central United States during June and July 1993.

Most of the events observed during The Great Flood of 1993 fit the Maddox et al.[4] composite for a frontal-type flash flood event. A southwest-northeast frontal boundary located below and to the south of the upper-level jet, shown schematically in Figure 3-6(a), acted to focus warm advection across the Plains and Midwest through the period. Each of the events was characterized by much stronger-than-normal, low-level, southerly jets that transported moisture northward into the front (Figure 3-8). The 850-mb winds and dew points and precipitable water values during the event exceeded the mean value found by Maddox et al. for frontal-type flash flood events.

---

[3] Uccellini, L.W., and D.R. Johnson. 1979. The coupling of the upper and lower tropospheric jet streaks and implications for the development of severe convective storms. **Mon. Wea. Rev.**, 107, 682-703.

[4] Maddox, R.A., C.F. Chappell and L.R. Hoxit. 1979. Synoptic and meso-α scale aspects of flash flood events. **Bull. Amer. Meteor. Soc., 60,** 115-123.

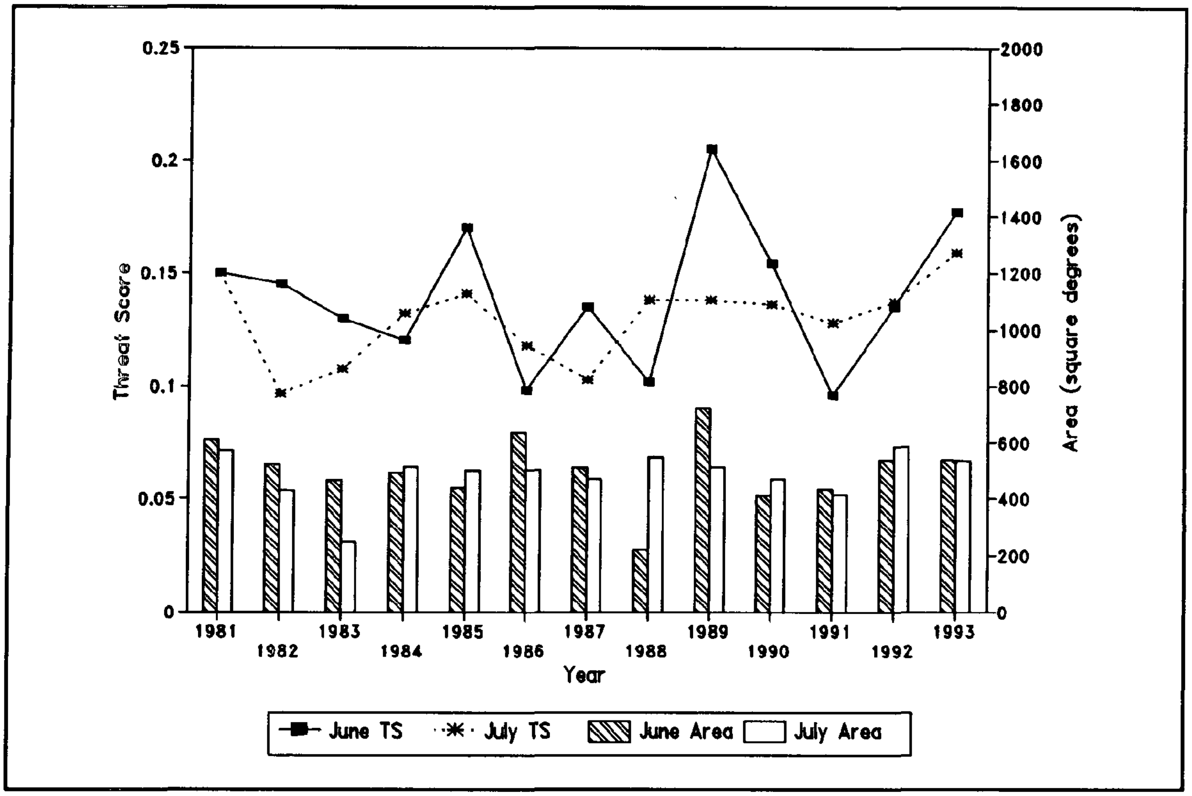


Figure B-1. *Monthly total 1-inch area measurements for June (left bar) and July (right bar) and the Threat Score attained by NMC forecasters.*

B.2.1 QUANTITATIVE PRECIPITATION FORECAST VERIFICATION SCHEME

Since 1961, NMC QPFs have been verified with an isohyetal areal verification scheme. This system provides measurements of the areas of the forecast and observed (analyzed) isohyets, and the area common to both, which is the correct area. These measurements are combined to compute the Threat Score (TS):

$$TS = A_c/(A_f + A_o - A_c)$$

A_c = Area Correct,

A_f = Area Forecast, and

A_o = Area Observed.

The analysis is based on available precipitation data including those in the River Forecast Centers' (RFC) precipitation files. The data are mapped to a grid which has a spacing that is 1/6 of the Limited Fine Mesh (LFM) model (about 30 km). Manual forecasts (and model forecasts for recent years) are interpolated to this same grid.

Figure B-1 shows the area covered by the observed 1-inch isohyet for each June and July since 1981, and the TS attained by the NMC forecasters. Nationally, both June and July 1993 were quite ordinary in terms of overall area covered by the 1-inch isohyetal analyses. The observed area over the United States for June and July 1993 was well within one standard deviation of the mean for these years.

The TS over the entire United States for manual forecasts was quite good. In July, forecasters set a number of records for 0.5- and 1-inch forecasts, while in June one record was set and several other records approached. Figure B-2 shows the daily TSs for a 1-inch threshold for the manual and the Regional Analysis and Forecasting System (RAFS) model forecasts for June and July, 1993. This graph is for the entire United States. However, reference to the individual cases which follow will show that scores, if available for the central United States, would be even better. Figure B-2 clearly shows the advantage of forecaster interpretation over raw model forecasts. In fact, for both June and July, the verification program shows that the monthly average TS of the forecasters' 36- to 48-hour, 1-inch forecast ("Day 2 forecast") is typically superior to the various models' Day 1 forecasts for the 1-inch isohyet.

The NMC QPF verification program covers the United States as an entity and does not yet include comparison of the ETA[5] model raw QPFs. Nationally, the Day 2 forecasts are virtually unbiased (i.e., the ratio of forecast areas to observed areas is near unity). On the other hand, statistics show that the Day 1 area bias varies from 1.2 to about 1.35 from month to month.

B.2.2 CASE STUDIES

Three case studies were selected to focus on heavy rainfall events that contributed greatly to flooding problems. The discussions include a brief overview of the synoptic situation including the models' mass field forecasts. This is followed by a discussion of QPFs and a comparison with observed precipitation. Each day includes: (1) the analyzed 24-hour rainfall ending at 12:00 UTC on the date indicated, with the analysis based on data retrieved from the RFC data files, (2) manual 24-hour QPFs for Day 1, and (3) 12- to 36-hour QPFs from the RAFS and ETA and AVN[6] models.

---

[5] ETA not an acronym. It stands for the Greek letter, ϵ, which is used in the mathematical formulation of the vertical coordinate system used in this model.

[6] AVN is not an acronym but stands for the AViatioN model.

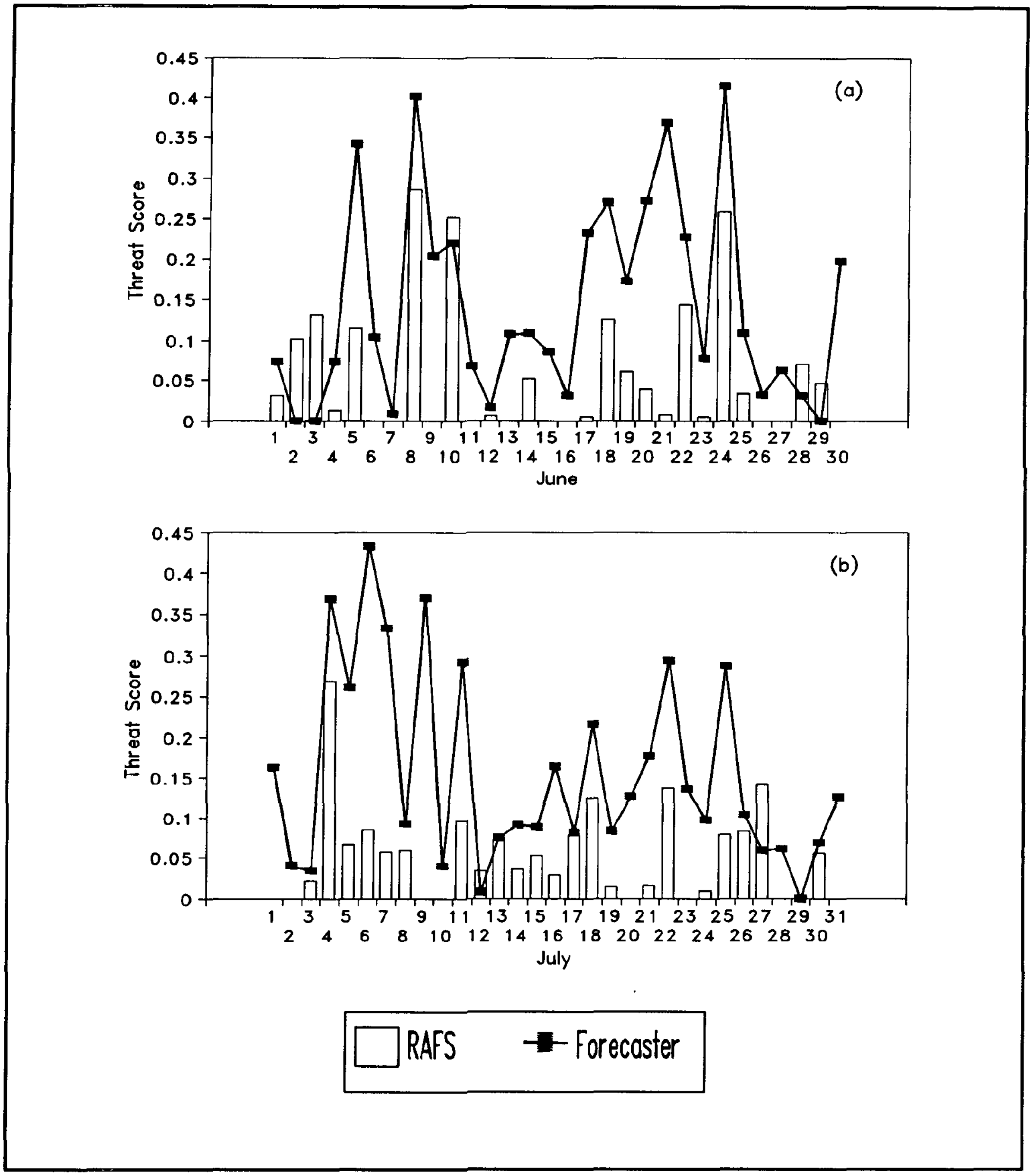


Figure B-2. *Daily 1-inch Threat Scores for (a) June and (b) July for NMC forecasters and for RAFS. The RAFS forecast for July 9 was not made.*

On the precipitation figures that are shown, analyzed isohyets are for 0.5 inch and multiples of 1 inch. The Day 1 manual forecast also includes a 0.25-inch isohyet, while the models include a zero line and central maximum values. Generally, on each day, the various model forecasts were extremely similar in their mass field forecasts and quite adequately represented the large-scale environment within which the precipitation events developed and were sustained. Thus, these fields are not shown.

B.2.2.1 REVIEW OF THE JUNE 17-19 RAINFALL EVENT

B.2.2.1.1 SYNOPTIC DISCUSSION

By 12:00 UTC, June 17, 1993, an unseasonable and very strong 500-mb trough had moved southeastward across the Pacific Northwest to Utah. This upper-level system moved into the central Rockies (Colorado) by the following morning, and by 12:00 UTC on June 19, it had moved slowly out over the western Plains of Nebraska. By June 19, it had weakened but was still a potent shortwave regarding its capability to trigger major rainfall activity. During the 24 hours before 12:00 UTC, June 17, 1993, low-level southerly flow of moist, unstable air had been reinforced by high pressure building southeastward from the Great Lakes to off the mid-Atlantic coast. In association with the major upper-level system, a surface low developed over the central High Plains, and a high pressure center settled in over Montana and the Dakotas with pressures above 1020 mb. All of these features combined to create a fairly strong frontal zone that generally stretched from southwest Nebraska into Wisconsin. This frontal zone began weakening on June 19 as the upper wave began to lose some of its strength.

B.2.2.1.2 FORECAST AND QPF DISCUSSION

The models handled the upper system quite well. At the same time, they displayed characteristic errors in overdeveloping the surface low over the western High Plains. To illustrate this point, at 12:00 UTC, June 17, the observed sea-level pressure gradient between Chicago and Sioux Falls was 6 mb. The RAFS 36-hour forecast, valid at 12:00 UTC on June 17 for this sea-level gradient, was 10 mb and the AVN 11 mb. Further examples of this sort of error may be found in: (1) the RAFS prediction of a 1003-mb center near North Platte on the 48-hour forecast valid 00:00 UTC, June 18; (2) the AVN forecast of a 998-mb low near Grand Junction; and (3) the ETA forecast of a 1002-mb low in southeastern Colorado. The verifying RAFS analysis for this time had a 1013-mb low in southwest Wisconsin. Sea-level pressures were 1016 mb at North Platte and 1011 mb at Grand Junction and southeast Colorado. Despite these errors in the low-level field, the models did provide some useful circulation guidance. Even though the models had excessive low-level inflow, their QPFs did not overpredict precipitation.

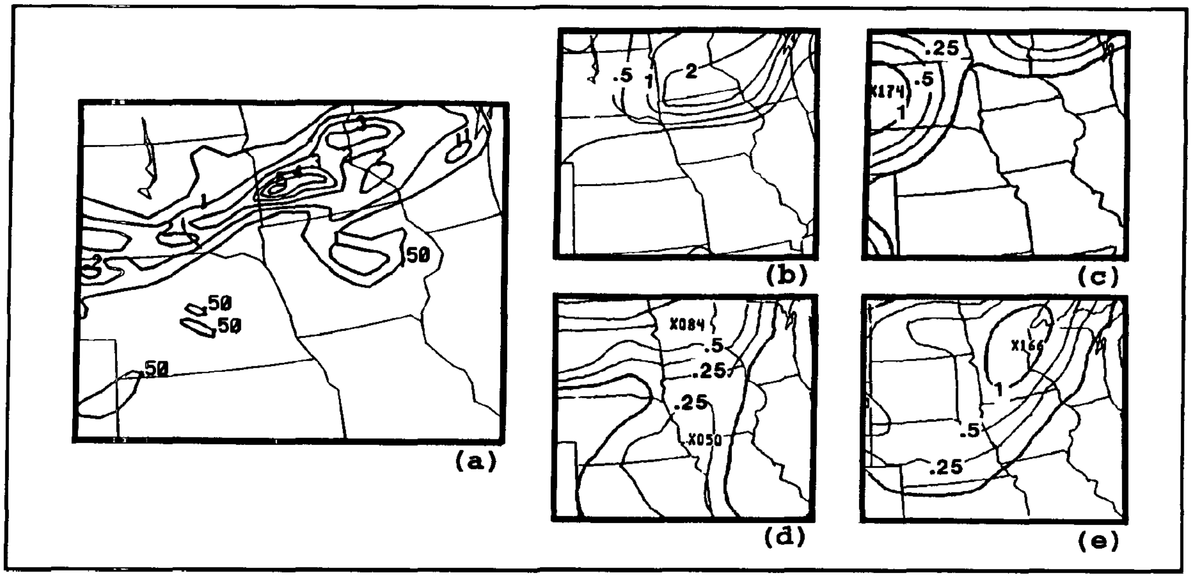


Figure B-3. *Rainfall for 24 hours ending 12:00 UTC on June 17: (a) observed, (b) manual forecast, (c) AVN forecast, (d) RAFS forecast, and (e) ETA forecast.*

Figure B-3 shows the array of observed and forecast rainfall maps for the first 24-hour period ending 12:00 UTC, June 17, 1993, with an analyzed 5-inch isohyet in Minnesota. The AVN 12- to 36-hour forecast, Figure B-3(c), showed this as a relative minimum region; the RAFS axis of maximum precipitation, Figure B-3(d), was too far north; and the ETA, Figure B-3(e), appears to be the better model in positioning the precipitation center, although the orientation of the area is incorrect. The manual QPF, Figure B-3(b), showed the extent of the 1-inch isohyet too far north but was very good on the rainfall axis in Minnesota.

Figure B-4 shows similar observed and forecast rainfall maps for the next 24-hour period, ending 12:00 UTC, June 18, 1993. The outbreak from the previous day continued northeastward into Wisconsin and new activity developed over the central Plains, with several 2- to 3-inch isohyets across Kansas and Nebraska. The RAFS forecast, Figure B-4(d), was wet but details were poor. Its maximum was in Iowa, exactly where the forecaster decided would be a good choice; the AVN forecast, Figure B-4(c), focused on South Dakota where observed amounts were less than 0.50 inch, while the Iowa-Minnesota portion was a reasonable forecast. The axis of the ETA in Figure B-4(e) was too far north in Nebraska but otherwise captured the observed axis quite well. The manual forecast, Figure B-4(b), was adversely affected by some of the model auxiliary output. As an example, the RAFS 24-hour vertical motion was +12 over western Iowa valid at 00:00 UTC, June 18, which, when considered in conjunction with other key model forecast parameters of strong southerly flow, strong low-level convergence and the

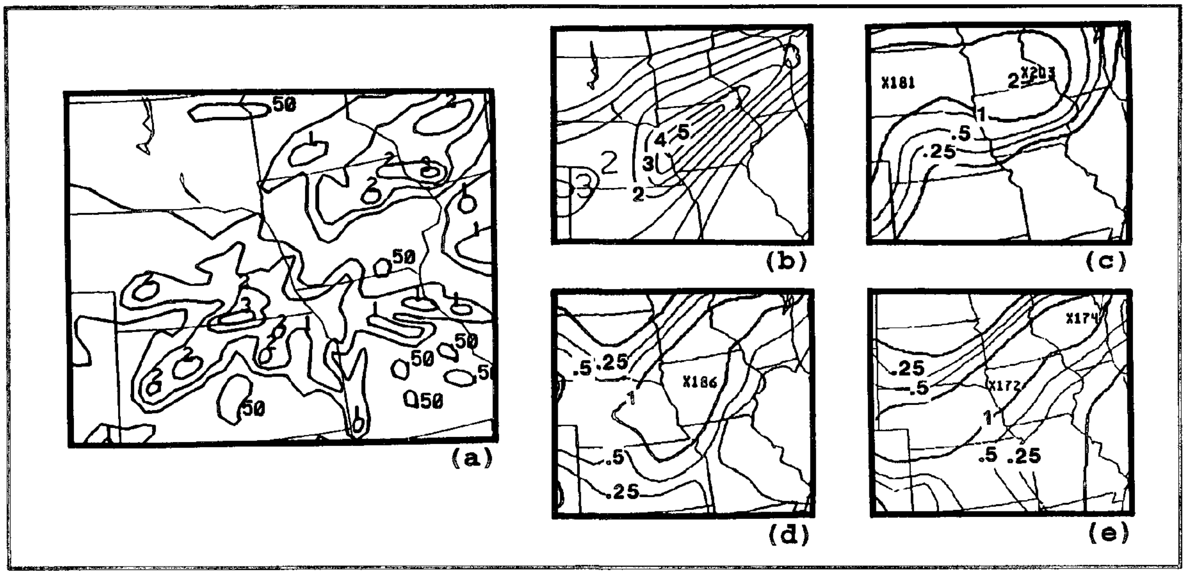


Figure B-4. *Rainfall for 24 hours ending 12:00 UTC on June 18: (a) observed, (b) manual forecast, (c) AVN forecast, (d) RAFS forecast, and (e) ETA forecast.*

presence of a jet streak[7], was very misleading to a forecaster. The QPF discussion that was issued at 6:40 a.m. EDT on June 17 highlighted the region for both the Day 1 and Day 2 periods, "Very dangerous and long duration flash flood event will continue the next couple of days over the central Plains...Upper Mississippi Valley area as excessive rainfall continues to drench this rain soaked area. Expect two-day rainfall totals in some areas to approach ten inches by Saturday morning." The plotted data showed some 2-day totals in central Kansas of 6-7 inches with nearly 6 inches in the Texas Panhandle.

The third day of this sequence is depicted in Figure B-5 and includes a rather large 1-inch area stretching from the Texas Panhandle northeastward into Wisconsin, with a significant number of 2- to 3-inch areas. The RAFS 1-inch forecast in Figure B-5(d) was primarily over northwest Kansas-Nebraska into northwest Iowa. Only the Iowa portion was realistic. The AVN, Figure B-5(c), placed its precipitation mainly in northwest Kansas, which again was poor with an unrealistic round shape. This guidance was easily discounted by an experienced forecaster. The ETA precipitation forecast, Figure B-5(e), was focused primarily in Nebraska-Iowa, although it did forecast 0.50 inch across Kansas. The forecaster, Figure B-5(b), predicted a realistic-sized 1-inch area but focused the maximum in southwest Iowa where a small area exceeded 2 inches. The excessive rainfall discussion that was issued at 10:30 a.m. EDT, June 18, 1993, stated, "Another day of heavy rainfall is expected across the Plains from Kansas and Nebraska across most of Iowa.... A favorable position along the right rear quadrant of an

[7] Jet Streak is a "local wind maxima embedded within the jet stream." (Palmen and Newton. 1969. **Atmospheric Circulation Systems**. Academic Press. [See Chaps. 4,5,8,9,13]).

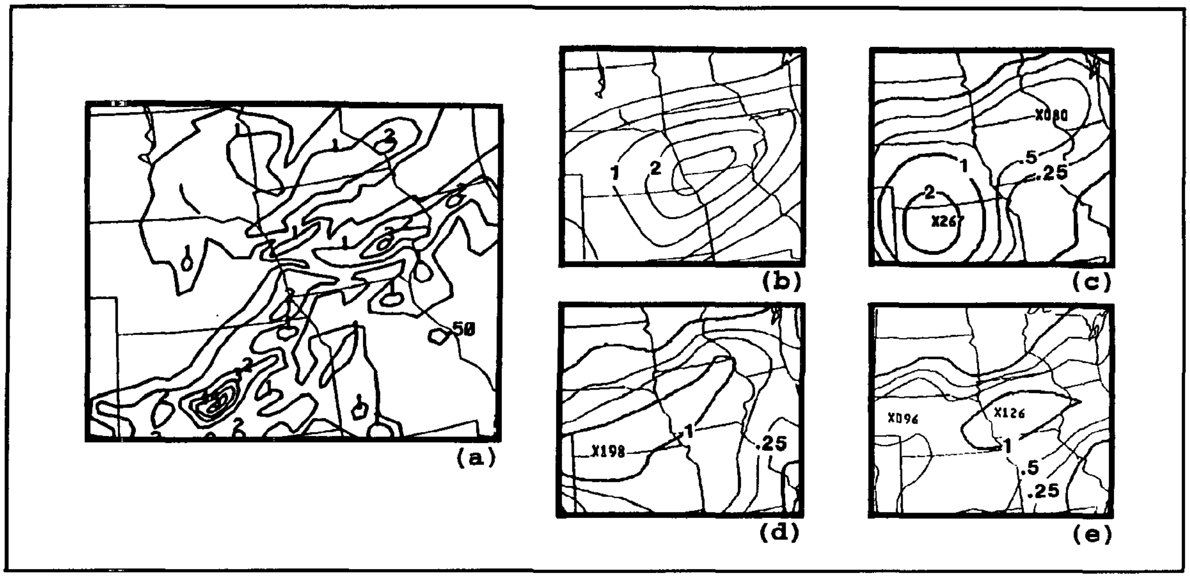


Figure B-5. *Rainfall for 24 hours ending 12:00 UTC on June 19: (a) observed, (b) manual forecast, (c) AVN forecast, (d) RAFS forecast, and (e) ETA forecast.*

upper-level jet streak would provide upper-level divergence and lifting across the region ... maximum rainfall is expected to be in the 3- to 5-inch range." Several reported values from central Kansas were 5-6 inches.

B.2.2.2 REVIEW OF THE JULY 4-9 RAINFALL EVENT

B.2.2.2.1 SYNOPTIC DISCUSSION

The most notable rains fell during the three 24-hour periods ending at 12:00 UTC on July 5, 7, and 9. The series culminated when 4-7 inches of rain fell over the Raccoon River basin and flooded the Des Moines water treatment plant (see Section 6.9). The discussion of this episode will focus on these three heaviest days.

A massive upper-level ridge was located over the eastern United States, and a mean trough was located over the High Plains and Rocky Mountains at 12:00 UTC, July 4 (similar to conditions shown schematically in Figure 3-6(a)). A strong cyclone developed to the lee of the Rockies and tracked into Manitoba as a potent jet streak moved across the Plains into southwestern Minnesota by 00:00 UTC, July 5. An unusually strong front associated with this low extended from Wisconsin southwestward across Iowa and Kansas to a much weaker surface low centered over the Texas Panhandle. A strong southwesterly pressure gradient existed between this low and the ridge in the east producing a strong low-level southerly jet. 850-mb winds of 20 m/s were located over Oklahoma, increasing to 20-25 m/s across Oklahoma and Kansas by 12:00 UTC, July 5. These 850-mb winds were much stronger than the mean values for the

June 5-July 19 period (Figure 3-8(a)). These winds transported abundant moisture northward with precipitable water values east and south of the front in the 1.8- to 2-inch range at 00:00 UTC, July 5, and to above 2 inches across northern Missouri and southern Iowa by 12:00 UTC, July 5.

The weak southern low tracked to northeastern Kansas by 12:00 UTC, July 5. The center of low-level inflow and strongest warm advection shifted across Kansas into Iowa. During this same period, an area of strong upper-level divergence developed along the right rear entrance region of the jet streak associated with the low in Canada. This upper-level divergence strengthened and shifted northeastward into Iowa. Along this same axis, a swath of rain 3 inches or heavier fell across Kansas, northwestern Missouri, and southern Iowa.

The heavy rains that fell during the period ending at 12:00 UTC, July 7, also occurred along the right rear quadrant of a jet streak. A stronger-than-normal, low-level jet was present with 20 m/s 850-mb winds directed into the frontal boundary across Missouri and Kansas. Strong low-level convergence associated with the low-level jet juxtaposed with strong upper-level divergence led to strong lifting along and just north of the front. A large area of rain 4 inches or heavier fell along the Missouri River in the state of Missouri.

The last widespread episode of very heavy rain during this series occurred across Iowa and eastern Nebraska, where strong upper-level divergence associated with the jet was juxtaposed with a potent overrunning pattern. The heavy rainfall was again associated with a stronger-than-normal low-level jet, the entrance region of an upper-level jet streak, and an east-west front. Southerly 850-mb winds of 20 m/s advected 18 °C dew points into Nebraska by 00:00 UTC, July 9. Precipitable water values exceeded 1.8 inches along the front. The series ended when the surface low tracked eastward from Kansas to Wisconsin, and the low-level jet pushed east of the area.

B.2.2.2.2 FORECAST AND QPF DISCUSSION

Model mass field forecasts for the deep, closed 500-mb low over western North Dakota, with an attendant deep (observed sea-level central pressure at 12:00 UTC, July 4, was 984 mb) surface low, were very good. The south-southwesterly low-level flow was very well forecast by the models, as was the position and depth of the low. All models overforecast the rain in Montana, which was correctly scaled back by the forecaster. The models all grossly underpredicted the rain which fell from Minnesota southwestward across the central Plains. The forecaster did a much better job of predicting this rainfall pattern. The ETA had the best model precipitation forecast.

By 12:00 UTC, July 5, the "vertically stacked" 500-mb and sea-level low centers (occluded cyclone) had moved to southwest Manitoba where, again, all models were extremely good with the mass field forecasts. Major rains occurred from central Kansas northeastward through southeast Iowa. This was associated with weak waves along the surface front in Kansas, with the waves being fairly well indicated by all models. Of particular note in Figure B-6, which

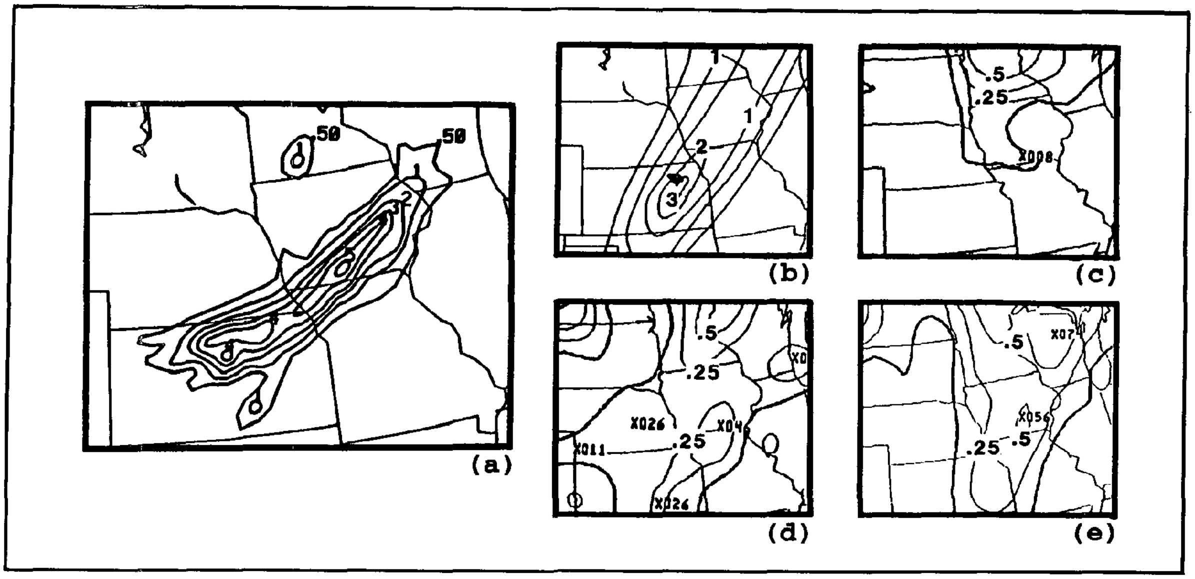


Figure B-6. *Rainfall for 24 hours ending 12:00 UTC on July 5: (a) observed, (b) manual forecast, (c) AVN forecast, (d) RAFS forecast, and (e) ETA forecast.*

shows the rainfall analysis for the 24 hours ending 12:00 UTC, July 5, is the poor effort by the models in predicting this rainfall event. The better model was the ETA (Figure B-6(e)), which showed about the right axis but underplayed the rainfall by about an order of magnitude. Despite the area of rainfall that did not occur in Wisconsin, the forecaster version was vastly superior to any model effort, as can be seen in Figure B-6(b).

Although this discussion focuses on the Day 1 QPFs that are issued early each morning, additional excessive rainfall potential outlooks are issued periodically. On the afternoon of July 4, one of these forecasts was issued that outlined eastern Kansas, southeast Nebraska, northern Missouri, southern Iowa, and southern Wisconsin for potentially excessive rains. The explanatory discussion, issued at 2:30 p.m. EDT, July 4, stated, "...rains are likely to be locally heavy to excessive...with 2- to 3-inch amounts possible in several hours and some 4- to 5-inch totals possible for the remainder this period. Heaviest rains are likely to lift northeast out of the southern/central Plains into Iowa-northern Missouri-southern Wisconsin by the end of the period."

The model circulation forecasts for the subsequent day (July 6) were very similar and strongly resembled the mean pattern shown in Figures 3-7(a) and 3-8(a). Again, the mass field forecasts were quite good in predicting the large-scale forcing environment. Even the model precipitation forecasts for this day (not shown), having failed to remotely catch the initial convective outbreak on the previous day, were good, as the major rain event of the previous day worked its way toward the Great Lakes.

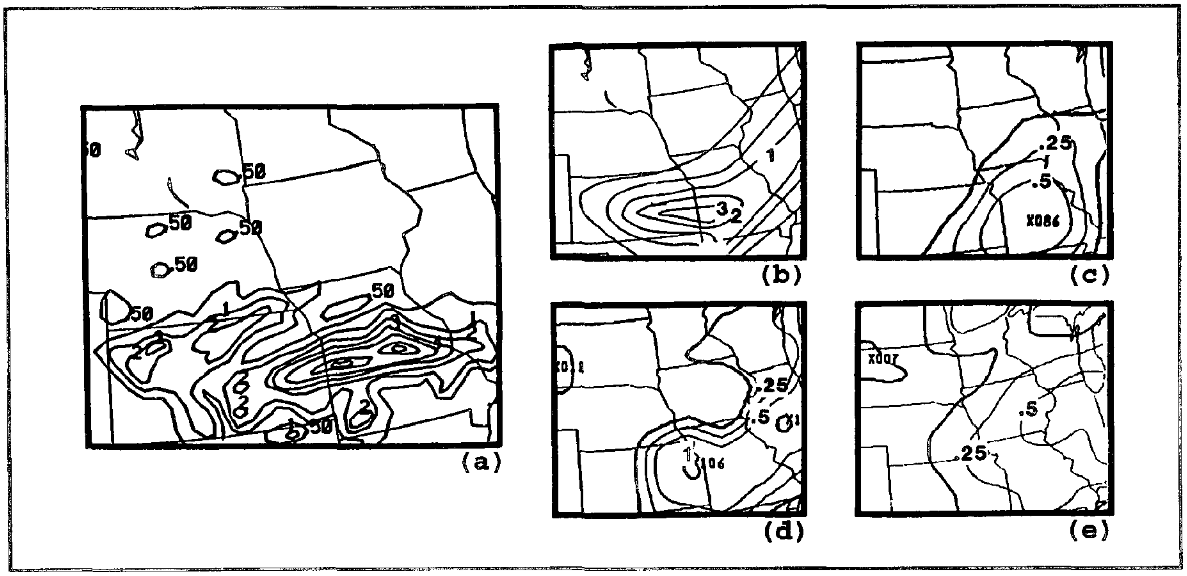


Figure B-7. *Rainfall for 24 hours ending 12:00 UTC on July 7: (a) observed, (b) manual forecast, (c) AVN forecast, (d) RAFS forecast, and (e) ETA forecast.*

The following 24 hours, ending at 12:00 UTC, July 7, had a major outbreak of convective rainfall across Kansas and Missouri with significant areas exceeding 5 inches in Missouri, as shown in Figure B-7(a). Two of the many parameters used by the forecasters to place and determine outbreaks of convective rainfall are the location of diffluent thickness patterns and favored 1000-500 mb thickness contours[8]. The ETA mass field forecast was better in this regard than the RAFS or AVN. The favored thickness region and a diffluent thermal pattern focused on eastern Kansas and Missouri. Despite that, the ETA provided some misinformation in the precipitation forecasts, as can be seen by comparing the ETA forecast in Figure B-7(e) to the observed pattern. The manually forecast QPF (Figure B-7(b)) featured an excellent axis and strong indications of excessive amounts. An excessive rainfall potential outlook discussion was issued at 10:32 p.m. EDT, July 6, for the remainder of the night until 12:00 UTC, July 7. This included a headline, "Life threatening flash flooding rains will continue to fall over the central Plains/mid-Mississippi Valley tonight." This narrative then went into the reasoning for expecting up to 5 inches of rain the remainder of the night over eastern Kansas and Missouri.

The 24 hours ending at 12:00 UTC, July 8, saw a respite to the onslaught of major precipitation events. Important rainfall continued over eastern Nebraska into Missouri, but heaviest amounts were generally not much more than 1 inch. The RAFS incorrectly moved its rain forecast into the lower Great Lakes; the AVN focused attention on eastern Iowa and Illinois, where rainfall

[8] Bohl, V.G., and N.W. Junker. 1987. Using climatologically favored thickness to locate the axis of heaviest rainfall. Nat. Wea. Dig., 12, No. 3, 5-10.

was less than 0.5 inch. The ETA placed its major rainfall area in Minnesota, where some rain fell, but the bulk of the rain was missed. The manually forecast QPF had a much better focus but also missed the details.

During the night of July 7-8, major computer outages due to power failures prevented any model runs except for the LFM. Little model guidance was available for the QPF for the 24-hour period ending 12:00 UTC, July 9, which was one of the single, major, 1-day events (Figure B-8(a)). The manual Day 1 QPF for this 24-hour period strongly focused on Iowa (Figure B-8(b)). This forecast must be considered as excellent, especially for a forecast that was issued 12-15 hours before a convectively driven rainfall event. At 2 p.m. EDT, July 7, the update forecast also focused attention on Iowa. The accompanying discussion headlined, "The broken record continues for the central states... as yet another day of heavy to excessive rains are likely... especially from northern Kansas/eastern Nebraska into much of Iowa and northern Illinois/southern Wisconsin." The text also included, "... there will easily be some 3-5 inch rains in spots... especially from northern Missouri/southern Iowa into west-central Illinois." At 9:40 p.m. EDT, July 8, an excessive rainfall potential forecast read, "Classical textbook flash flood event unfolding over eastern Nebraska/Iowa this evening. Evening radiosonde observation data show tremendous upper features supporting extremely heavy rainfall through tonight. Surface boundary across the region will be the focus for convective development .... expect rainfall rates of 2-4 inches in a few hours with overnight totals nearing 10 inches in some areas of eastern Nebraska to central Iowa."

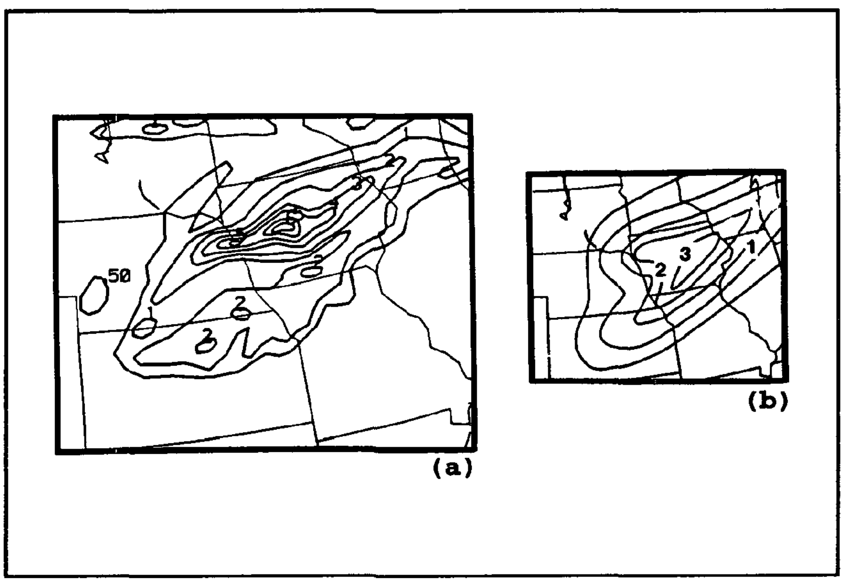


Figure B-8. *Rainfall for 24 hours ending 12:00 UTC on July 9: (a) observed and (b) manual forecast.*

B.2.2.3 REVIEW OF THE JULY 21-25 RAINFALL EVENT

B.2.2.3.1 SYNOPTIC DISCUSSION

A strong shortwave kicked eastward from the mean trough and lifted across the northern Rocky Mountain region on July 21-22, lowering the pressure to the lee of the mountains. By 00:00 UTC, July 22, an area of lower pressure extended from eastern Colorado northward across eastern Wyoming and Montana into Canada. This trough of lower pressure and a surface high over the western Great Lakes region, which formed in a region of confluent upper-level flow, combined to strengthen the southerly gradient across the Plains. The southerly winds associated with this gradient had two effects. They advected important moisture into Kansas and provided a favorable pattern for overrunning north of the east-west frontal boundary. A Maddox frontal-type heavy rainfall event that developed across Kansas in the area of strong isentropic lift produced over 4 inches of rain by 12:00 UTC, July 22.

An even heavier event occurred during the next 3 days with over 15 inches of rain reported across southeastern Nebraska. This 3-day period is examined in a little more detail. The southerly gradient weakened slightly by 12:00 UTC, July 22, but reintensified as another upper-level wind maximum punched eastward and helped induce cyclogenesis over western Kansas at 00:00 UTC, July 23. The position of the low on July 23 mirrors the position of the low for the mean pressure pattern during June 5-July 19 (Figure 3-6(a)). South of the front 850-mb winds strengthened from around 10 m/s at 00:00 UTC, July 23, to 15 m/s at 12:00 UTC, July 23. The magnitude of the southerly 850-mb winds during this period was significantly higher than the mean values during June 5-July 19 (Figure 3-8(a)). The stronger-than-normal southerly (15-20 m/s) low-level jet remained almost stationary through 00:00 UTC, July 25.

The rather stationary character of the low-level jet can be explained by the presence of an area of low pressure to the lee of the Rockies through the entire event. The center of the low pressure tried to shift eastward across Kansas and Nebraska between 00:00-12:00 UTC, July 23, as one weak upper-level impulse shifted out of the Rockies; but the center reformed again over Kansas as a new upper-level wind max and associated shortwave approached later on July 23. The low deepened to 1004 mb over western Kansas by 12:00 UTC, July 24, as the next and even stronger shortwave started to move eastward from the mean trough. During the entire 4-day sequence, the low tried to shift eastward across Kansas more than once but kept reforming westward as each new upper-level impulse ejected from the mean trough. The low did not move out of Kansas until after 00:00 UTC, July 25, when a major shortwave shifted eastward away from the mountains.

An axis of very moist, unstable air stretched from the Gulf Coast states northward into Kansas at 12:00 UTC, July 21. Precipitable water values within this axis ranged from 1.8 across Kansas to over 2 inches along the Gulf Coast. By 12:00 UTC, July 22, the precipitable water values had risen to over 2 inches across Missouri. The deep moisture led to K-indices[9] in the 36-40 range; and by 00:00 UTC, July 23, K-indices had risen to above 40 while lifted indices[10] were -8 to -12. Both the K-indices and precipitable water values were higher than the mean values that Maddox et al. found for frontal-type events.

Analyses of the moisture flux at 850 mb every 6 hours from 12:00 UTC, July 22, through 00:00 UTC, July 25 (not shown), indicated an axis of stronger moisture transport aimed at southeastern Nebraska, where as much as 5 inches of rain was reported each day.

The strong low-level jet and strong thermal and moisture gradient associated with the front resulted in a concentrated area of wet-bulb potential temperature[11] advection at 850 mb during each 12-hour period of the event. The advection of warm, moist air at low levels acted to keep the air mass unstable. The axis of heavy rainfall corresponded well with an axis of low-level moisture convergence.

B.2.2.3.2 FORECAST AND QPF DISCUSSION

The initial outbreak in this sequence (not shown) occurred across central Kansas during the nighttime period ending 12:00 UTC, July 21, 1993, with several reports of 3.5-4 inches. The AVN did not predict much rain in Kansas, the RAFS defined some of the axis of rain in western Kansas, and the ETA showed a small 1-inch isohyet with a fairly good envelope. On the other hand, the 1- and 2-inch isohyetal area estimated by the forecaster was a little too large.

The subsequent 24-hours ending 12:00 UTC, July 22, 1993, Figure B-9(a), showed some individual totals near 5 inches in east-central Kansas and 3-3.5 inches in northeastern Kansas. The AVN, Figure B-9(c), poorly defined the rainfall forecast; the RAFS, Figure B-9(d), made a gallant attempt with a 1-inch isohyet in Nebraska and Iowa; and the ETA, Figure B-9(e), confined its main rainfall to Nebraska. The forecaster, Figure B-9(b), correctly included eastern Kansas, western Missouri, and southeast Nebraska in the 1-inch or greater area.

---

[9] The following is the mathematical definition of the K-index.
(850-mb temperature) - (500-mb temperature) + (850-mb dewpoint) - (700-mb dewpoint depression):

$$K = T_{850} - T_{500} + T_{d850} - (T - T_d)_{700}$$

(Note that 500-mb temperature is always negative and thus makes a positive contribution to K-index.)

[10] The lifted index is defined as the difference (in degrees Celsius) between the observed 500-mb temperature and the temperature of a parcel of air if it were lifted adiabatically from a low level to 500 mb.

[11] The wet-bulb potential temperature is the temperature an air parcel would have if cooled from its initial state adiabatically to saturation and thence brought to 1000 mb by a saturation-adiabatic process. This temperature is conservative with respect to reversible adiabatic changes.

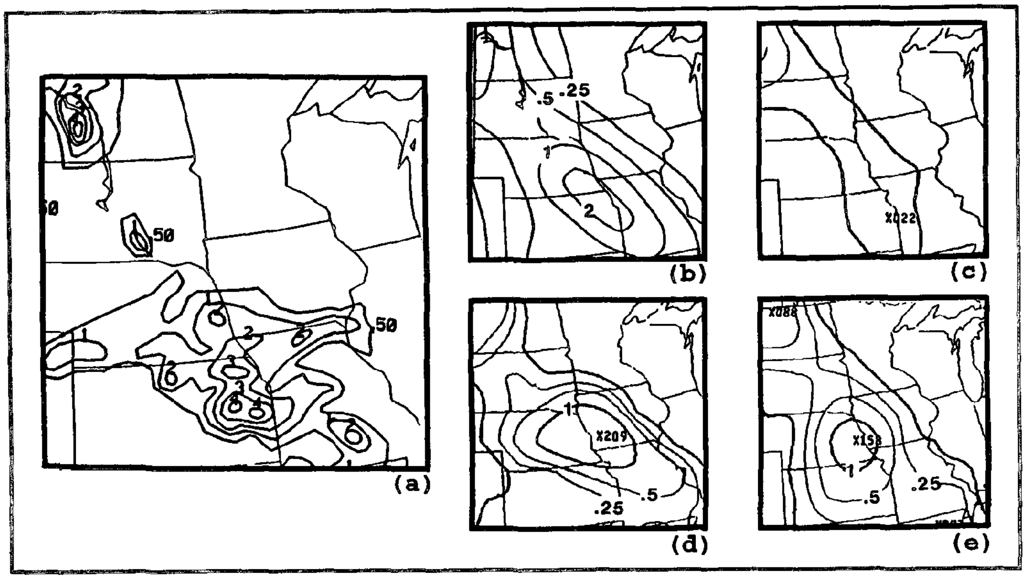


Figure B-9. *Rainfall for 24 hours ending 12:00 UTC on July 22: (a) observed, (b) manual forecast, (c) AVN forecast, (d) RAFS forecast, and (e) ETA forecast.*

Over the next 3 days, portions of southeastern Nebraska received rainfall amounts totaling 10-15 inches. Since some observations are missing, it is difficult to know the exact totals. At this point, it is appropriate to quote from the Extended Forecast Discussion that was issued at 3:30 p.m. EDT on July 20, 1993, "What this means is that over the next 5 days...portions of especially Iowa, Kansas and Missouri could easily receive 6-12 inches of new rainfall". It is most unusual to mention specific amounts of rain in this discussion, which is usually issued by categories. For the specific 24-hour period ending July 23, 1993, the focus of the observed rainfall became southeastern Nebraska, Figure B-10(a). The three models did little to highlight this specific region, Figure B-10(c-e). The forecaster did but was a little bit too far east, Figure B-10(b); and overall, the forecast area was much too large, mainly with its southward extension through Missouri.

During the 24-hours ending 12:00 UTC, July 24, individual amounts up to 6 inches were reported from the southeastern corner of Nebraska, Figure B-11(a), and important rainfall occurred in northern Illinois. The models did a remarkably poor job--the RAFS, Figure B-11(d), showed a large 1-inch isohyet, which was virtually completely outside of the 0.5-inch analyzed area; the AVN's 0.5-inch isohyet, Figure B-11(c), was completely outside of the observed 0.5-inch area; the ETA, Figure B-11(e), fared a little better but not by much. The forecaster, Figure B-11(b), showed knowledge of a major event but was either a little too far north for the Nebraska event or too far west for the Illinois event. The forecaster also showed more knowledge of the events in the Dakotas than the models.

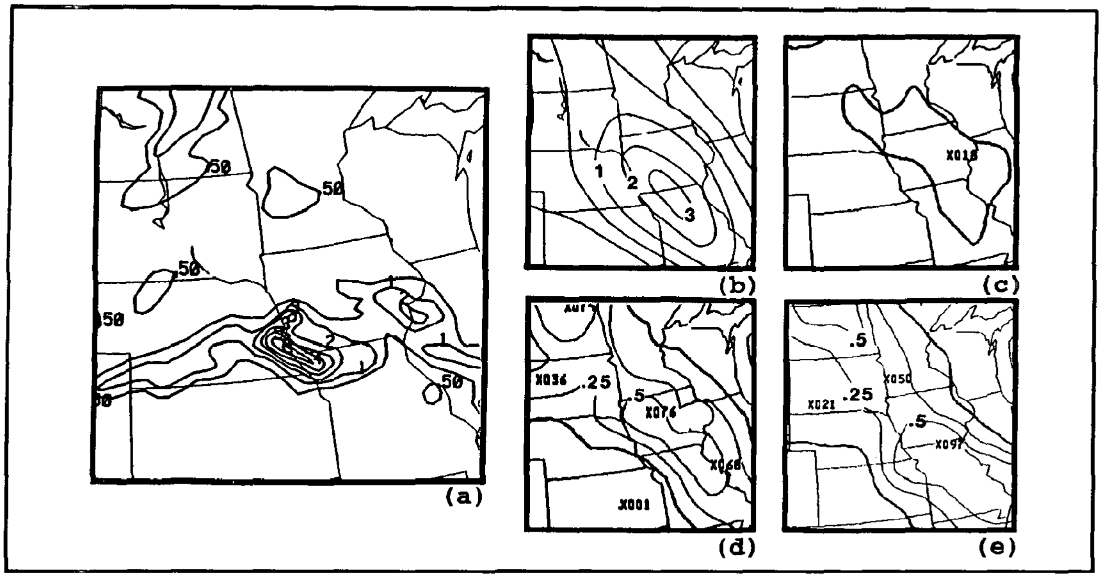


Figure B-10. *Rainfall for 24 hours ending 12:00 UTC on July 23: (a) observed, (b) manual forecast, (c) AVN forecast, (d) RAFS forecast, and (e) ETA forecast.*

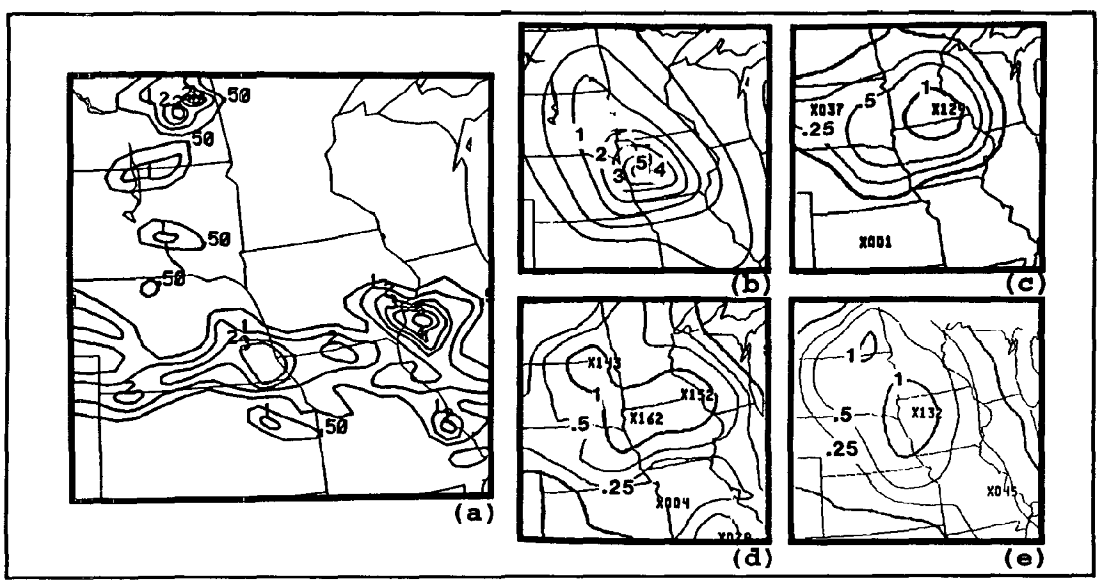


Figure B-11. *Rainfall for 24 hours ending 12:00 UTC on July 24: (a) observed, (b) manual forecast, (c) AVN forecast, (d) RAFS forecast, and (e) ETA forecast.*

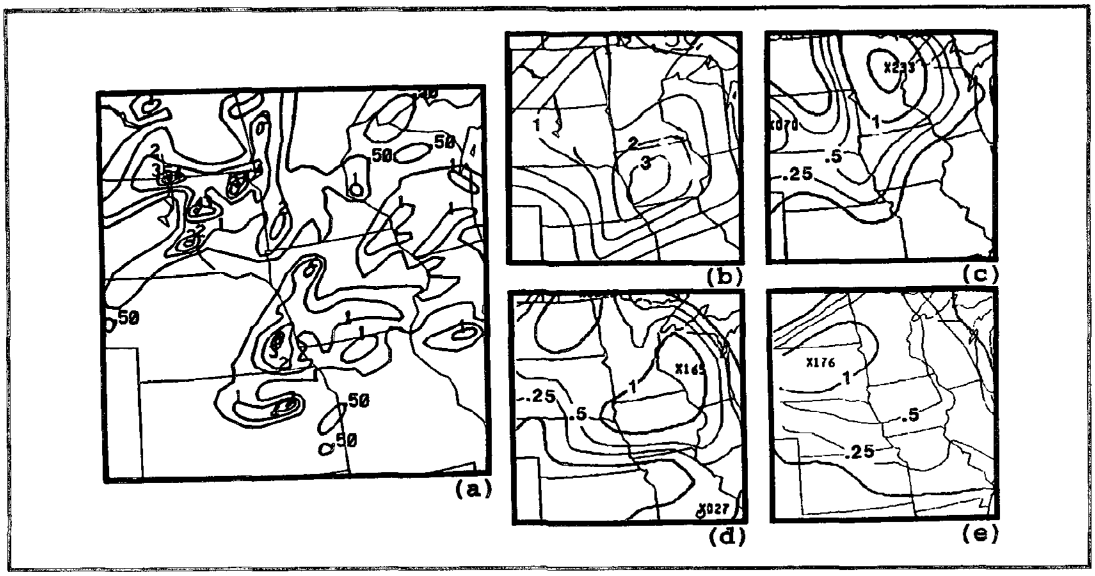


Figure B-12. *Rainfall for 24 hours ending 12:00 UTC on July 25: (a) observed, (b) manual forecast, (c) AVN forecast, (d) RAFS forecast, and (e) ETA forecast.*

On the final day of the sequence, ending 12:00 UTC, July 25, the AVN, Figure B-12(c), finally produced some precipitation--a maximum of 2.33 inches near Duluth which, unfortunately, was in the analyzed minimum. Without going into each detail, the overall shape of the forecaster 1-inch isohyet, Figure B-12(b), clearly showed emphasis over eastern Nebraska-Iowa, with a secondary focus in the Dakotas. This was a much better definition than any of the models.

B.2.3 SUMMARY AND CONCLUSIONS ON QUANTITATIVE PRECIPITATION FORECASTS AND MODELS

The numerical models all did a good job of defining the large-scale forcing environment except, as noted, for a few small problems with respect to circulation forecasts. These are characteristic errors of each model, which forecasters are well aware of and which were compensated for in the manual forecasts. The details from the models, particularly with respect to precipitation and the timing of events, was less than desired. It has been shown that the NMC forecasters provided guidance forecasts that were overall substantially better than the models. Clearly, the 24-hour QPFs, which are issued about 6 a.m. EDT about 12-18 hours in advance of the typical nocturnal convective precipitation events, do not completely capture all of the details that occur. Quotes from some of the excessive rainfall discussions and other narratives clearly showed, however, that the NMC forecasters were very aware of the events prior to their occurrence. The major flooding which occurred in the central United States was not the result of a daily heavy rainfall event/flash flood but rather resulted from the sum of many days of heavy rains, which correlate nicely with the data shown in Figures 3-7 and 3-8. Figure B-2 showed the TSs for the forecaster compared to the RAFS and clearly establishes the vital role that is played by

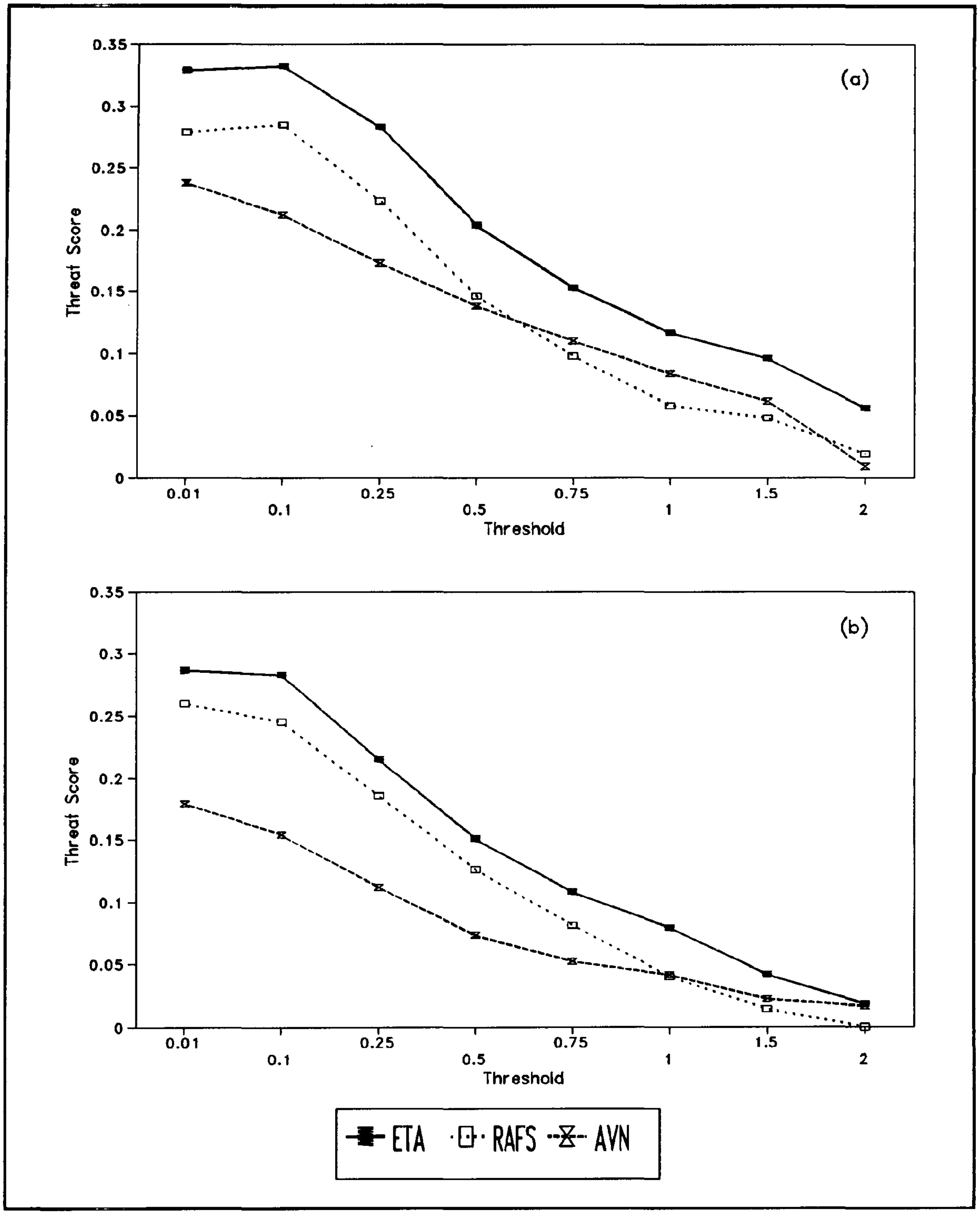


Figure B-13. *Comparative model verification for the RAFS, ETA, and AVN in terms of the Equitable Threat Score: (a) June 1993 and (b) July 1993.*

the NMC forecaster in the QPF process. The continued updating of information also clearly showed the need, both prior to and during an event, for extensive and continued dialogue between field hydrologists, meteorologists, and NMC forecasters.

During the discussion of the models, it was commonly noted that the ETA was perhaps the best of all the models in forecasting the rainfall patterns. Figure B-13 shows the different model gridpoint verifications for various rainfall thresholds. This figure uses the Equitable Threat Score, which is similar to the usual TS; however, this score removes any effects that might occur from a random-chance forecast. For very low frequency occurrence events, such as 1 inch of rain, the differences between the TS and the equitable TS are negligible. Figure B-13 shows these scores for June and July for the AVN, RAFS, and ETA models. For the 1-inch forecast (also for other values), the ETA shows a clear edge over the other models.

The NMC verification program will be undergoing some changes in the near future. As adequate resources become available, the ETA 24-hour forecast fields will be added to the verification statistics. The entire verification project will be ported to a workstation where regionalization of results and computation of additional and useful statistics will be possible. Finally, 6-hour forecasts will be verified in a similar areal manner as are the 24-hour forecasts.

B.3 HYDROLOGIC ANALYSES OF SELECTED QUANTITATIVE PRECIPITATION FORECASTS

The preceding discussion amply demonstrates that significant skill often exists in QPFs. However, these forecasts are not currently used on a routine basis in river forecasting. This section examines some reasons why this is the case.

NMC forecasters demonstrated an excellent ability to predict the general location and magnitude of extreme rainfall events experienced during The Great Flood of 1993. The skill level is highest at the synoptic scale[12]; considerable skill exists to scales as small as, or somewhat smaller than, a typical midwestern state. At these scales, individual convective events are not delineated. As shown above, the models and especially the forecasters are quite successful in identifying general regions of excessive precipitation. But, as discussed in the preceding sections, the positioning of the QPF centers is a continuing challenge for NMC forecasters. Limits in spatial and temporal resolution of observations, limits in numerical modeling capabilities, and limits in scientific understanding all make it impossible to provide highly specific QPFs (in terms of the positioning of the smallest rainfall centers).

On the other hand, as indicated in Chapter 4, current river forecast modeling systems are designed for input on the basis of subbasins that are much smaller than the current ability for QPFs to specify. This inherent "scale mismatch" between the spatial scale, where QPFs show

[12] A synoptic scale feature is one comparable in size to a mature, winter cyclone, or 600-1,000 miles.

their best skills, and the scale needed as input to river forecast models will continue to be a challenge to the meteorological and hydrologic forecasters.

Comparisons between QPF and observed precipitation in this section are based on volumes of water, either predicted or observed, in contrast with areal precipitation coverage above a threshold, as used in computing the TS. In addition, the comparisons in these sections are made at a finer resolution than the national scale used for the TS computations. Indeed, as shown in Figure B-1, on a national scale, June and July 1993 precipitation was quite ordinary--hardly the case in the upper Mississippi basin! A volumetric comparison is most meaningful in terms of input to hydrologic models: river forecasting is based essentially on an accounting system that tracks the volume of water as it flows through the basins being modeled/forecasted.

Section B.3.1 compares QPFs with observed precipitation amounts for 21 selected days during this event, including all the days discussed in the case studies of Section B.2. This is followed by a more detailed comparison between QPF and observed precipitation at the scale of a state (Section B.3.2). Iowa was chosen for this purpose, as it was one of the hardest hit states, both in terms of precipitation and flooding. Finally, a briefer comparison between QPF and observed precipitation is made in Section B.3.3 for the basins contributing to the flooding that led to the closing of the water treatment plant in Des Moines. This case overlaps with both the QPF case study discussed in Section B.2.2.2 and the hydrologic case study in Section 6.9.1.

B.3.1 STATE-SCALE COMPARISON OF QUANTITATIVE PRECIPITATION FORECASTS AND OBSERVED PRECIPITATION

A rough comparison was made between: (1) NMC's operational (manually analyzed) 24-hour QPF (Day 1 forecast) and (2) NMC's manually analyzed observed 24-hour precipitation. As discussed above, the first analysis is NMC's best estimate of future precipitation based on the output from several models, as well as individual forecaster judgment and experience. The second analysis includes observed data from the NWS's surface aviation observation network, all automated data used by RFCs, and available cooperative observer data.

Five major flooding episodes were chosen for analysis: (1) major-to-record flooding along the Minnesota River, (2) development of a significant flood crest on the upper Mississippi River, (3) propagation and intensification of the flood crest downstream into the middle Mississippi River, (4) development of a record flood crest on the Raccoon and Des Moines Rivers in and near the city of Des Moines, and (5) development of a near-record-to-record flood crest along the lower Missouri and middle Mississippi Rivers.

Rainfall events that contributed to these flooding episodes during The Great Flood of 1993 were then defined: (1) June 17-19, (2) June 23-24, (3) July 1-11, and, (4) July 21-25. This resulted in a total of 21 days for which precipitation data were analyzed.

For each day, two maps (NMC's operational QPF, and NMC's manual analysis of observed precipitation) were digitized for a nine-state area, including North and South Dakota, Nebraska,

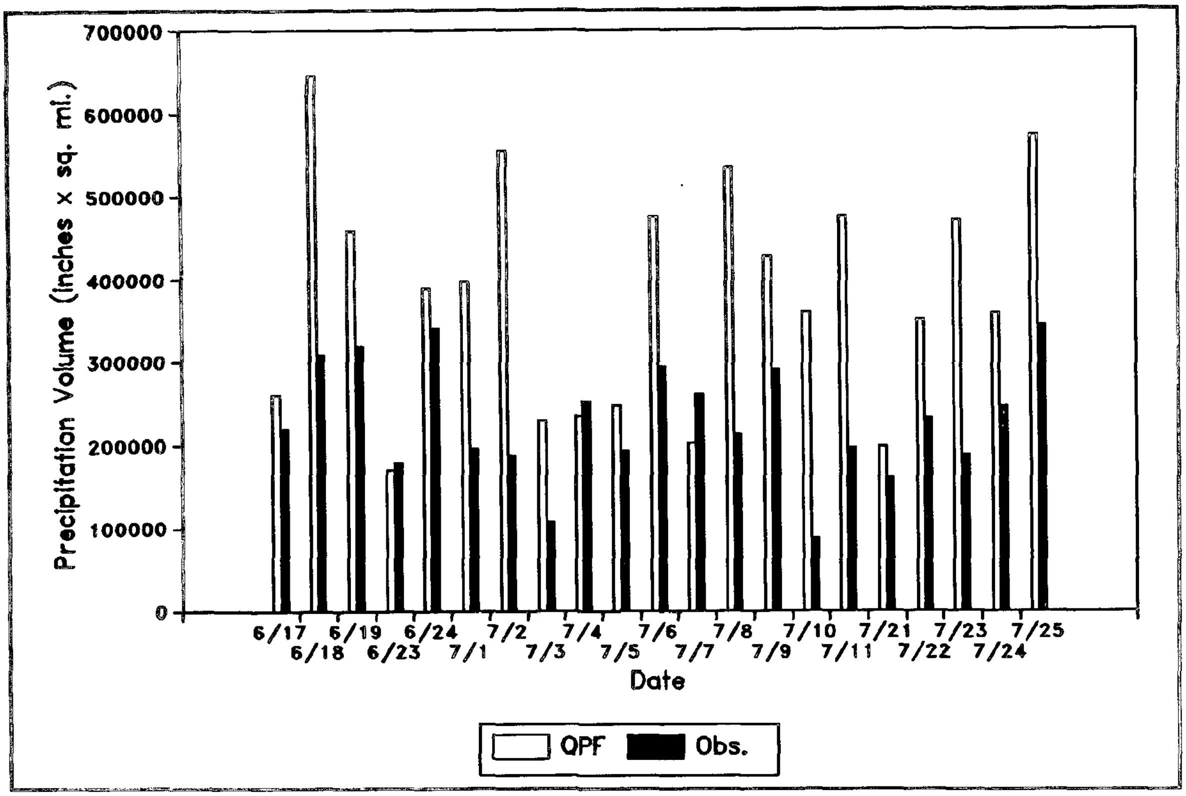


Figure B-14. *Comparison between precipitation volumes calculated from QPF and observations for the nine-state area impacted by The Great Flood of 1993.*

Kansas, Minnesota, Iowa, Missouri, Wisconsin, and Illinois. Prior to digitizing, one difference was noted between these two analyses: the QPF maps are analyzed beginning with a 0.25-inch isohyet, while the observed precipitation maps are analyzed beginning with a 0.50-inch isohyet. Thus, to ensure an internally consistent comparison, the 0.25-inch isohyets on the QPF maps were **not** digitized. Therefore, all precipitation calculations were made only for the heavier amounts that fell or were predicted to fall within the 0.5-inch isohyet.

After digitizing all 42 maps, both predicted and observed precipitation volumes--product of the precipitation depth (in inches) and the areal extent (in square miles)--were calculated for each of the nine states affected by the flooding for each of the dates chosen.

Figure B-14 shows predicted precipitation volume (QPF) compared to observed precipitation volume for each of the 21 "key" precipitation days, summed over the entire nine-state area. It is clearly evident that for these 21 selected dates, QPF was higher than the observed precipitation on all days except 3 (June 23, July 4, and July 7). A positive correlation (0.43) exists between the predicted and the observed.

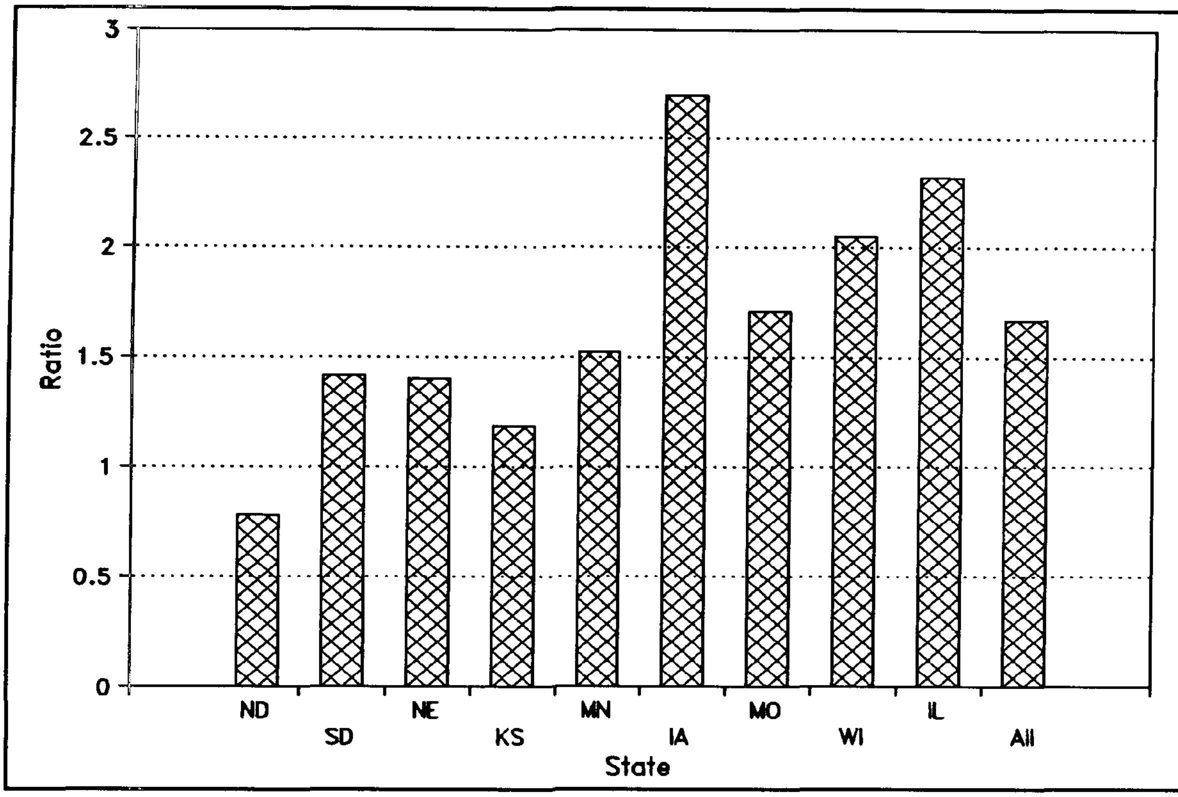


Figure B-15. *Ratio of QPF to observed precipitation volumes for a summation over the 21 days indicated in the text.*

Figure B-15 shows the ratio of predicted precipitation volume (QPF) compared to observed precipitation volume for the 21-day totals over each of the nine states, as well as the ratio for the entire nine-state area. The ratios range from 0.79 in North Dakota (the only ratio less than one) to 2.7 in Iowa. The overall average is 1.65. These ratios imply a bias higher than indicated in Section B.2.1. One possible reason for this discrepancy is that the sample used here is quite small and may not be representative of longer-term statistics. Also, the TS used by NMC compares areas above a given threshold and does not reflect the spatial variations in magnitude within the selected threshold. The TS does not fully and accurately account for the **volume** of precipitation that results from precipitation amounts in excess of whatever threshold is selected. High-intensity cores, which account for substantial portions of the total storm volume, are crucial in river forecasting, in particular for situations that repeatedly occur or persist for long durations. The record crests observed during The Great Flood of 1993 came about from the cumulative effect of many intense precipitation cores over a long period of time (see Sections 3.3.1 and 3.3.2).

B.3.2 DETAILED COMPARISON BETWEEN QUANTITATIVE PRECIPITATION FORECASTS AND OBSERVED PRECIPITATION FOR IOWA

The period of July 1-11, 1993, over the state of Iowa, was selected for more detailed study. Both the observed and the QPF isohyetal patterns were interpolated to a grid of discrete points spaced about 1 mile apart. At each of these grid points, the ratio of the QPF to observed precipitation was calculated. An example of the two input fields, as well as the resulting ratio field for July 9, is shown in Figure B-16. QPF (Figure B-16(a)) showed a southwest-northeast oriented maximum of 3 inches or more. The observed precipitation (Figure B-16(b)) showed a more east-west oriented axis, with peak values about double that indicated by QPF. Figure B-16(c) shows that the underprediction was focused in the west-central part of the state. At the same time, areas in both the northwest and southeast portions of the state experienced less precipitation than was indicated by QPF. The median of some 55,000 ratios of QPF to observed precipitation was 1.38, indicative of the fact that QPF overpredicted the total volume of water falling in Iowa on this day.

It is interesting to note that this overprediction occurred in spite of QPF not identifying the observed rainfall centers above 3 inches (see Figure B-16(b)). While these centers show extremely high rainfall amounts, their areal extent is rather compact. On the other hand, the QPF 2-inch isohyet (Figure B-16(a)) covers much of the state, whereas the corresponding observed areal coverage is much smaller. In this example, QPF was too broad in its delineation of the 1- and 2-inch isohyets and was not able to delineate the centers of heaviest precipitation.

Similar analyses were performed for each of the first 11 days in July. The results are summarized in Figure B-17. The horizontal tick shows the median value of the more than 55,000 grid point ratio estimates. The vertical line for each day encompasses the ratios falling between the 25th and 75th percentiles. Not shown on this figure are ratios for July 3, 7, and 10. On both July 3 and 10, no significant precipitation (greater than 0.5 inch) was observed in Iowa, while QPF values ranged from 0.25 to 2 inches on July 3 and from 0.5 to 4 inches on July 10. On July 7, there was no rainfall and QPF also did not predict significant rain. The average ratio for the 8 days shown is 1.6. If July 3 and 10 were factored in, this ratio would be higher still. Again, as in Section B.3.1, this analysis suggests that QPF may systematically produce estimates that exceed observed values while at the same time failing to delineate intense rainfall centers. Only one day selected (July 4) had a median ratio significantly less than one.

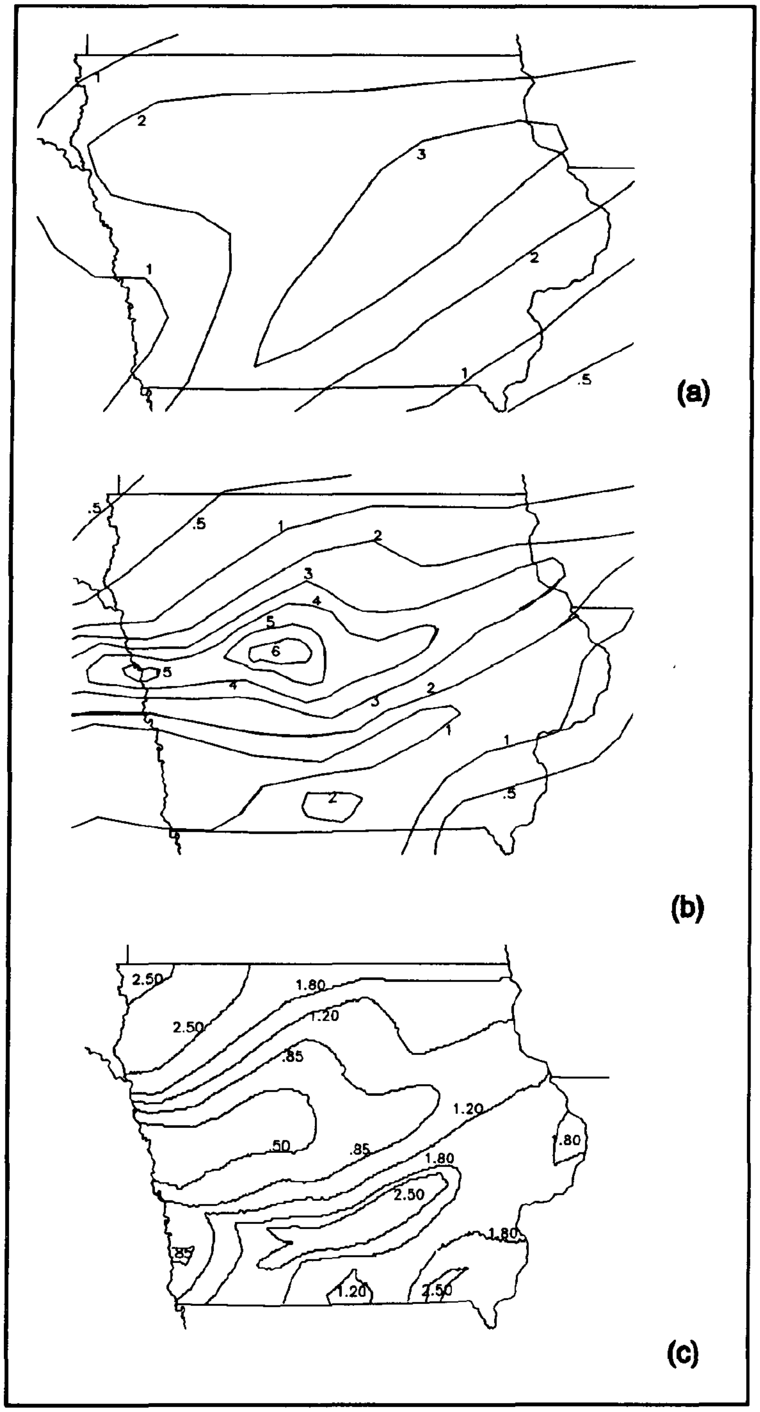


Figure B-16. *Spatial variation of precipitation in Iowa on July 9, 1993: (a) QPF, (b) observed, (c) ratio of QPF to observed.*

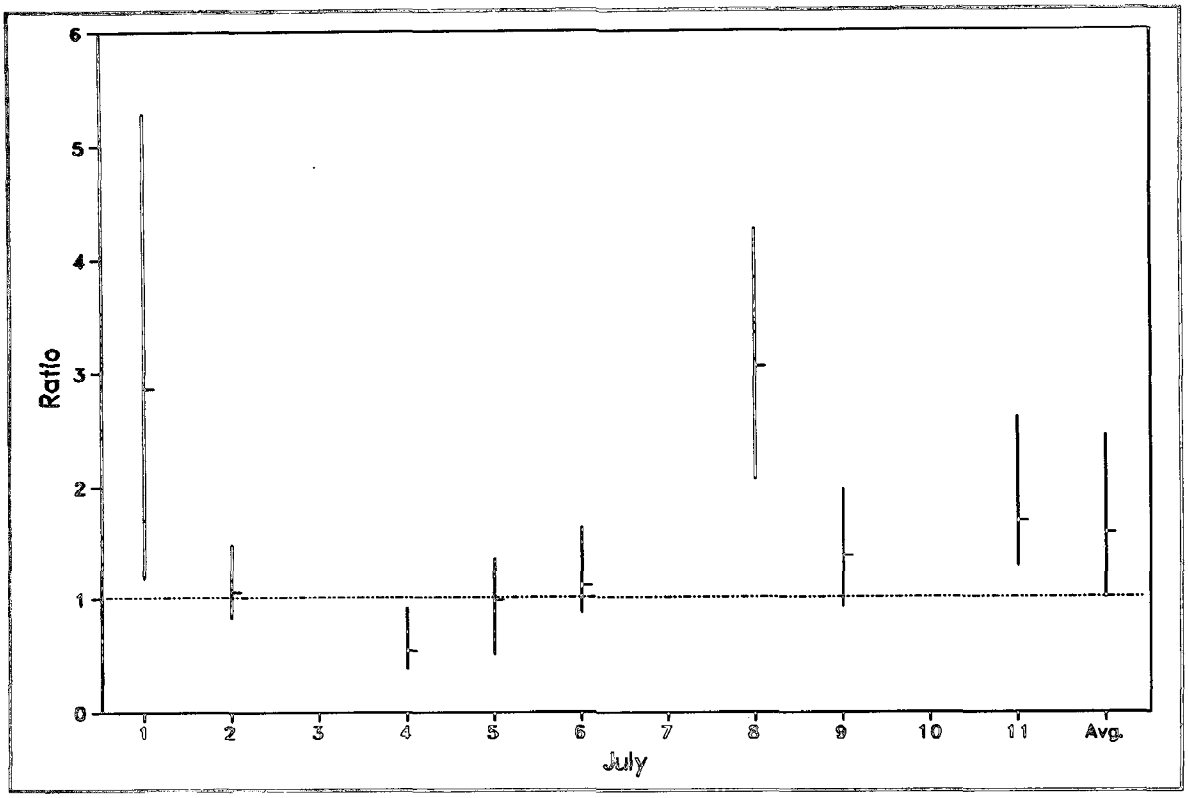


Figure B-17. *Ratio of QPF to observed precipitation in Iowa for each of the first 11 days in July and the average for the 8-day period (July 3, 7, and 10 excluded).*

B.3.3 COMPARISON BETWEEN QUANTITATIVE PRECIPITATION FORECASTS AND OBSERVED PRECIPITATION FOR SUBBASINS ABOVE DES MOINES

Figure B-18 is a map of the subbasins used to compute river stage forecasts in the Des Moines area. (See also the case study in Section 6.9.1.) Using both QPF and observed precipitation, volume estimates were made for July 8-11 over each of these subbasins. The comparison between these two estimates for the 4-day total is shown in Figure B-19. Again, the 4-day QPF total consistently exceeds the observed precipitation amounts for each subbasin; however, the positive correlation (0.98) between forecast and observed is remarkably good for the 4-day aggregation. The average ratio over the entire 4-day period for all subbasins is 1.4. Figure B-20 shows the same volumetric ratios for the total precipitation that fell over all the basins shown in Figure B-18 for each day of the 4-day period. On July 8, 10 and 11, QPF characteristically overforecasted the volume of water, especially on July 10 when QPF predicted substantial precipitation and no significant rainfall was observed. However, on July 9, the region received about double the volume of water predicted by the QPF.

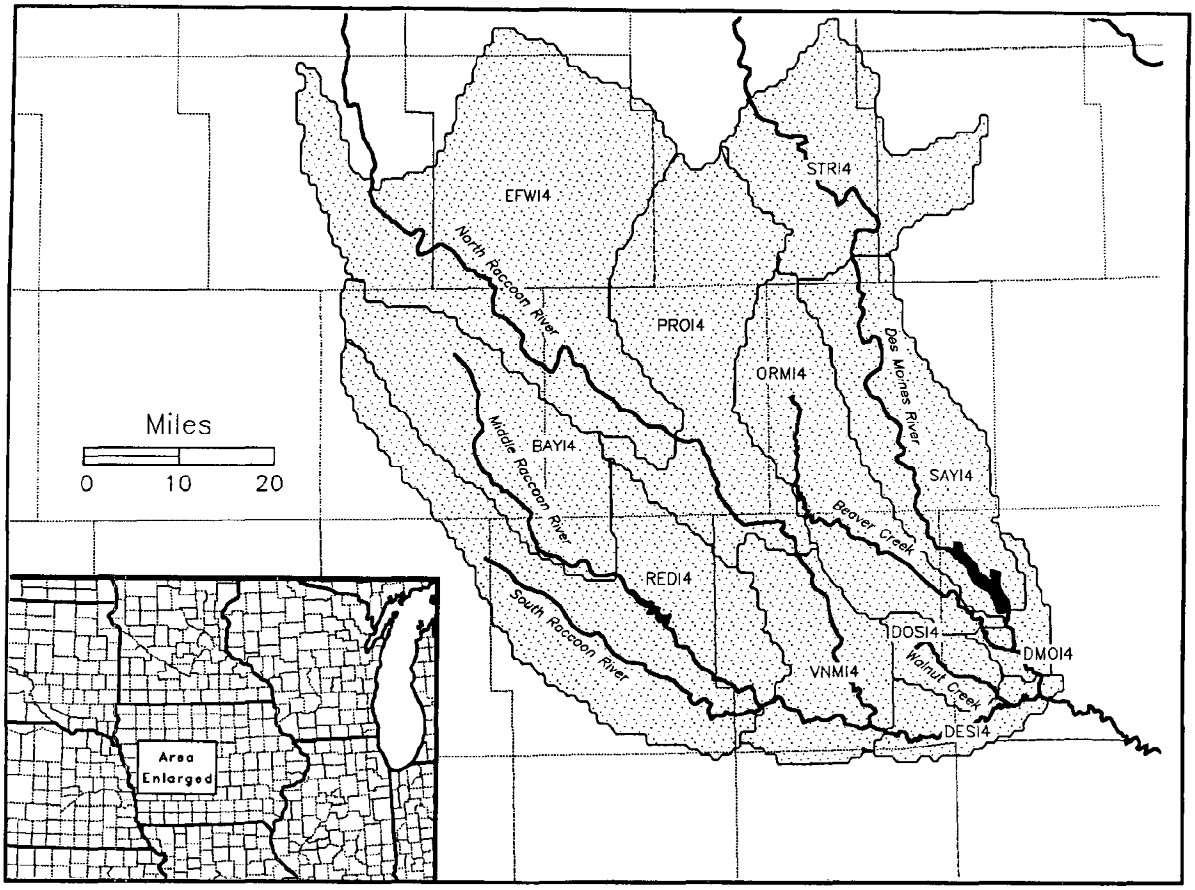


Figure B-18. *Subbasins used to calculate river stages in the Des Moines area.*

B.4 MONTHLY AND SEASONAL PRECIPITATION OUTLOOKS

NMC also produces 30- and 90-day precipitation outlooks. (See Figure B-21 for examples.) Especially for major floods that last for months (or during prolonged droughts), use of such information could prove highly beneficial to long-term forecast accuracy. Sections 6.4.2 and 6.5.2 showed the significant errors that resulted on the Mississippi and Missouri Rivers when extended forecasts did not include the June through August deluge. As shown in Figure B-21, the 30-day outlook for July clearly indicated increased chances of above-normal precipitation. Had this information been incorporated into the long-term forecast procedures, the degree of underestimation should have been reduced. A prerequisite for routine use of such outlooks in river forecasting algorithms is the systematic assessment of their accuracy.

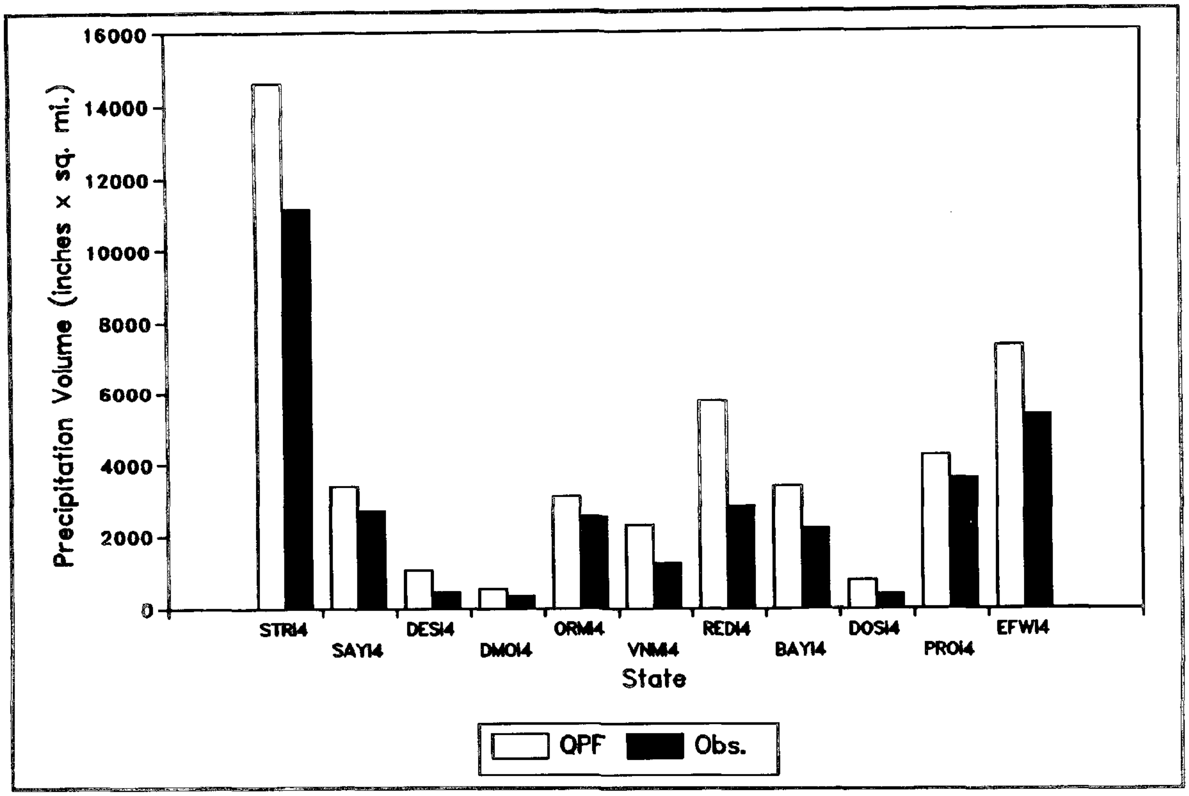


Figure B-19. *Comparison of 4-day (July 8-11) total volume of water computed from QPF and observed precipitation for basins above Des Moines. See Figure B-18 for location and boundaries of each basin.*

Current widely used operational procedures do not lend themselves to incorporation of this type of probabilistic outlook. However, systems based on ESP techniques[13] could accommodate information such as that presented in these outlooks. ESP provides probability forecasts based on historical hydrometeorological data used with advanced (physically based) meteorological and hydrological models. Such forecasts will provide water and emergency managers with an ability to incorporate forecast uncertainty in their decisions.

Techniques could be developed to condition the probability distribution of the historical series of hydrometeorological data by weighting the data series according to the outlook patterns. This would enhance long-term river forecasts. While these techniques would not predict all-time record flooding levels produced by future meteorological events well outside the historical range, such as observed in The Great Flood of 1993, they could produce forecasts that indicate

[13] Day, Gerald N., and Edward J. VanBlargan. 1983. The use of hydrometeorological data in the NWS Extended Streamflow Prediction program. Fifth Conf. Hydromet., Tulsa, Oklahoma, American Meteorological Society.

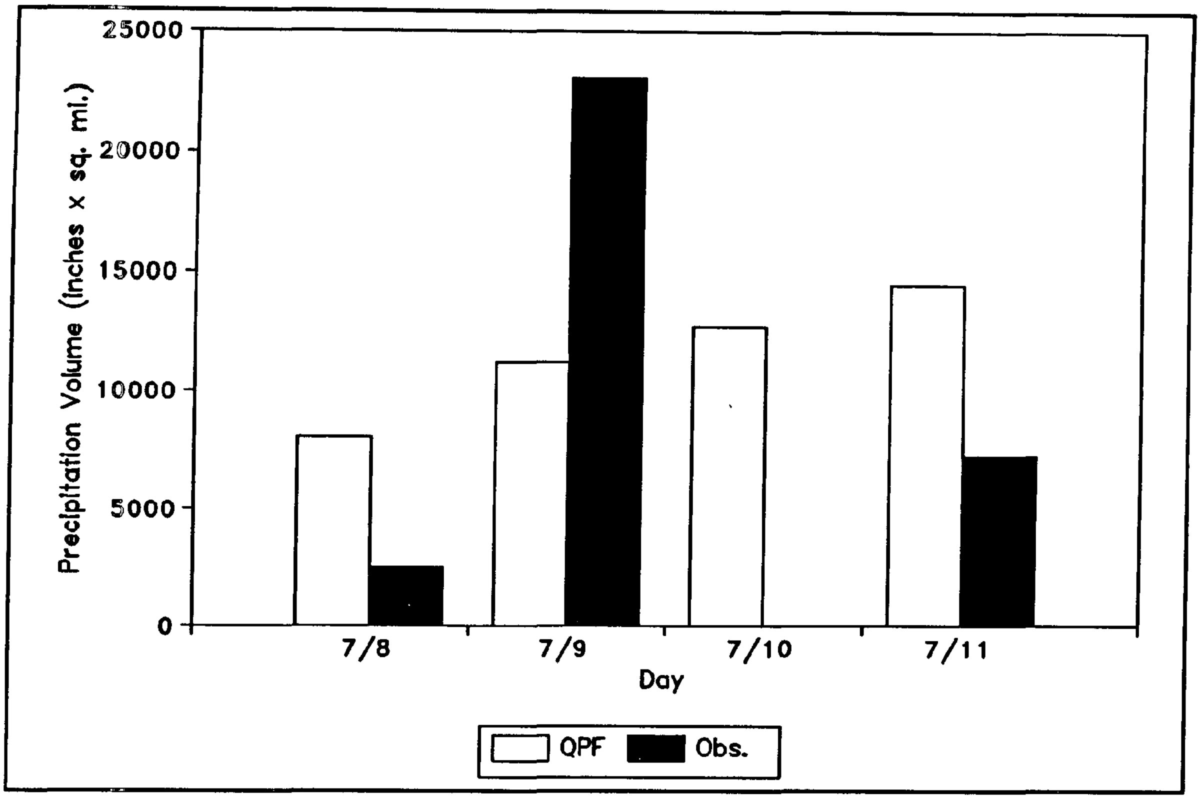


Figure B-20. *Comparison of daily total volume of water over 11 basins above Des Moines computed from QPF and observed precipitation.*

significant probabilities of flood levels approaching record levels of the past. Incorporation of long-term precipitation outlooks into river forecasts within an ESP framework could provide credible ranges of future flood stages, allowing emergency management agencies at all levels of government to better prepare for flooding. The probability range of the forecast would provide an indicator of the level of risk. The technique would also be highly effective in identifying the likelihood of when the flood would recede. Finally, this same system would be quite useful to water managers. They could make risk-based decisions in their operation of water management structures, such as reservoirs, that could optimize use of limited water supplies, especially in areas such as the western United States. It is estimated that nationwide implementation of an advanced hydrologic modeling system based on ESP techniques would cost less than $15 million per year and would save the Nation more than $100 million per year.

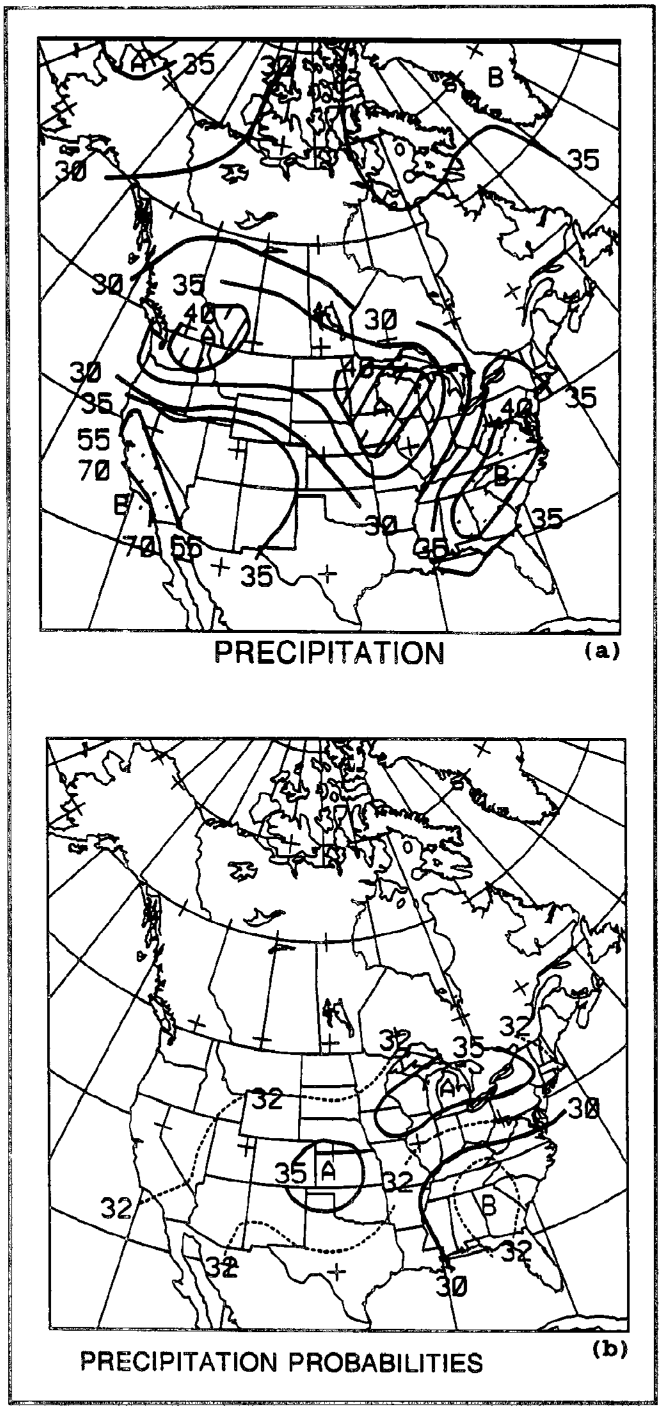


Figure B-21. *Examples of NMC precipitation outlooks for (a) 30 days (July 1993) and (b) 90 days (July-September 1993).*

B.5 SUMMARY AND CONCLUSIONS

NWS river forecasting models currently used for the upper Mississippi and Missouri River basins do not routinely and objectively take advantage of QPF. One reason for this is limitations in the forecast system infrastructure. There is now no efficient way to translate QPFs into subbasin input quantities needed by the river forecast models. This function, along with preparation of detailed observed precipitation estimates based on *in situ* gages, radars, and satellite information, will be accomplished by the Hydrometeorological Analysis and Support functions at each RFC in the modernized Weather Service.

A more significant problem with incorporating QPF into river forecast models is the inherent scale mismatch. As discussed above, the scientific complexity in predicting rainfall from small-scale convective cells makes detailed positioning of high-intensity rainfall centers beyond our current scientific capabilities. This problem increases as both the duration of the forecast interval and target area (i.e., subbasin) decrease and as the forecast period moves further into the future. The limited analyses in Sections B.3.2 and B.3.3 suggest that, in spite of biases (which are probably tractable), the random variation of QPFs from day-to-day and/or basin-to-basin can be quite large (see Figure B-20). This creates a significant challenge to incorporate QPF information into the current river forecast system. Despite this challenge, it is important to use the QPF in hydrologic forecasting since QPFs demonstrated a high level of skill in predicting the persistence of unprecedented precipitation events that led to The Great Flood of 1993. As discussed above, the ESP framework is key to accomplishing this task.

Through the ESP approach, it may be possible to overcome the limitations in current application of QPF to river forecast procedures. As outlined in Section B.4, the ESP approach is ideally suited to incorporating outlooks such as those routinely prepared by NMC. If reasonable uncertainty levels can be inferred for 3- to 5-day and 6- to 10-day categorical outlooks, the ESP framework could also be used to incorporate this information into river forecasts. Finally, if the scale mismatch between QPF and hydrologic models can be better characterized in probabilistic terms, it may be possible to describe the effect of smaller scale precipitation fluctuations around the QPF on the uncertainty in future hydrologic conditions.

APPENDIX C

USE OF SATELLITE DATA DURING THE GREAT FLOOD OF 1993

Rod Scofield and Rao Achutuni

C.1. GEOSTATIONARY SATELLITE IMAGERY

The geostationary satellite has the unique ability to observe the atmosphere and its cloud cover from the global scale down to the storm scale, frequently and at relatively high resolution, through its instrument complement of sounders and imagers. This makes the geostationary satellite an important tool for weather analysis and forecasting including diagnosing flash floods. Floods are multiscale and concatenating events which occur on scales from "global scale" to "synoptic scale" to "mesoscale" and finally to the "storm or event scale." Conceptual models and satellite features have been developed to diagnose systems on all meteorological scales that, through the process of multiscale interaction, lead to flash floods.

On the global scale to synoptic scale, the 6.7 μm water vapor imagery detects northward movements or surges of mid- to upper-level moisture from the tropics into the mid-latitudes. These surges are called water vapor plumes and are usually associated with large-scale circulations (Scofield, 1991, 1990b; Thiao, 1993). As the plumes move northward into the United States, they often become coupled with low-level, moist, unstable air and upper-level forcing mechanisms, such as jet streaks[1]. These interactions often result in flash floods. Such was the case during the Upper Midwest floods of this past summer where water vapor plumes persisted on the back side of the subtropical ridge (located over the eastern United States), and jet streaks repeatedly occurred on the western and northern boundary of the plume. An example of a water vapor plume and rather large Mesoscale Convective System (MCS) over Iowa and Missouri (at M) is shown in Figure C-1. Jet streaks were located over Kansas and Minnesota. Over northern Missouri, 5-7 inches of rain occurred with this system.

[1] Jet streak is a "local wind maxima embedded within the jet stream." (Palmen and Newton. 1969. **Atmospheric Circulation Systems.** Academic Press [see Chaps. 4,5,8,9,13]).

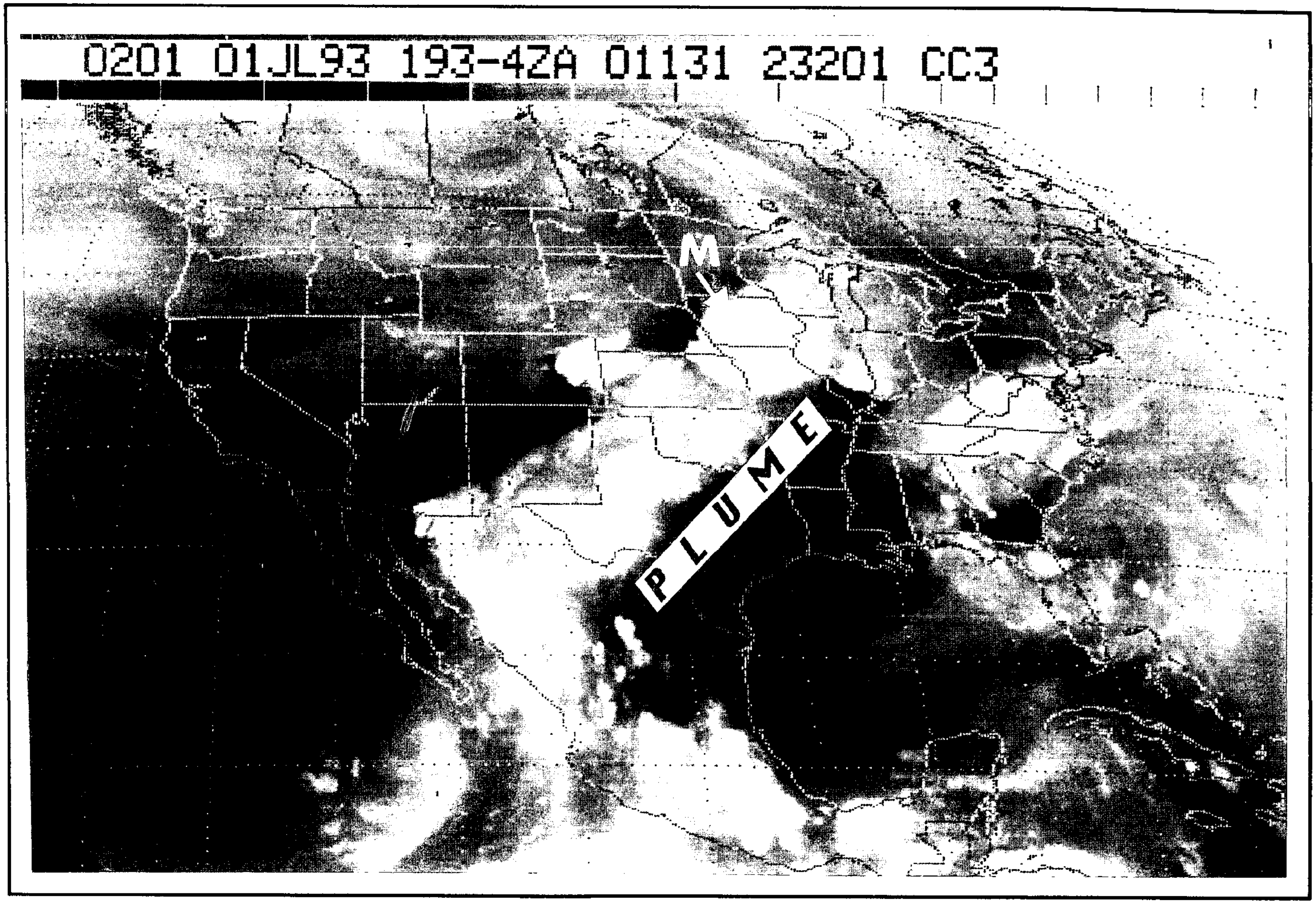


Figure C-1. *6.7 μm water vapor imagery for 9 p.m. CDT, June 30, 1993 (02:00 UTC, July 1). Note water vapor plume (labeled PLUME on photo) and Mesoscale Convective System (labeled M).*

On the synoptic scale and mesoscale, the water vapor plume along with the high equivalent potential temperature (θ_e) air can produce MCSs if acted upon by a forcing mechanism, such as a jet streak. A water vapor plume and an accompanying jet streak (at J-S) are helping to produce the MCS (at M) and flash floods over Minnesota in Figure C-2.

For this same event over Minnesota, on the mesoscale and storm scale, the enhanced infrared imagery (Figure C-3) depicts a rapidly growing MCS (at A). This MCS merges with smaller convective systems to the west (at C); the result is a back-building MCS (at B). Back-building MCSs often prolong the heavy rainfall and cause flash floods, e.g., 5-7 inches of rain over southern Minnesota. MCSs, such as the one over southern Minnesota, often feed back to the larger scales by producing outflow boundaries. In this case, the visible imagery shows that an outflow boundary was produced ("dashed lines" in Figure C-4). This helped to create new convection and continued the heavy rainfall over Iowa and Minnesota. On the storm scale, the intensity, movement, and propagation of thunderstorms are used to determine how much, when, and where the heavy rain is going to move during the next 0-3 hours.

The Synoptic Analysis Branch (SAB) of the National Environmental Satellite, Data and Information Service (NESDIS) makes satellite rainfall estimates nationwide whenever heavy rains are threatening to produce, or are already producing, flash flooding (Borneman, 1988). SAB meteorologists monitor the growth trends of thunderstorms on the GOES-7 geostationary satellite imagery using techniques developed by Scofield and Oliver (1977, 1987) to quantify rainfall estimates. In support of the National Weather Service (NWS), estimates are disseminated over the Automation of Field Operations and Services (AFOS) system in an alphanumeric message called "SPENES" directed to the affected area through the alarm/alert feature of the AFOS system. In addition to the estimated amounts of rainfall, the message also contains information on trends as seen in the satellite imagery and short-range forecasting (nowcasting) information. Estimates are done on the Interactive Flash Flood Analyzer (IFFA) that is part of the VAS Data Utilization Computer (VDUC) system located at the National Oceanic and Atmospheric Administration (NOAA) Science Center in Camp Springs, Maryland. IFFA-derived graphics products are sent to the River Forecast Centers (RFC) in Fort Worth, Texas, and Slidell, Louisiana.

Throughout June, July, and August of 1993, large- and small-scale convective systems passed over the Midwest almost daily contributing to the devastating flooding. SAB precipitation meteorologists logged over 900 hours during this period monitoring the convection for heavy rainfall and issuing satellite rainfall estimates. Around 400 satellite rainfall messages were issued to the NWS Central Region, most of which were for rains that contributed to the flooding. This represents 50-80 percent of the total workload for the SAB precipitation meteorologists for that 3-month period. There were 29 cases documented where over 5 inches of rain were estimated in a 24-hour period over the Upper Midwest. Statistics computed over the past several years have shown that the current technique underestimates extreme rainfall events (5 inches or more in a 24-hour period) and overestimates the lighter events (2 inches or less). However, these statistics are computed from relatively dense rain

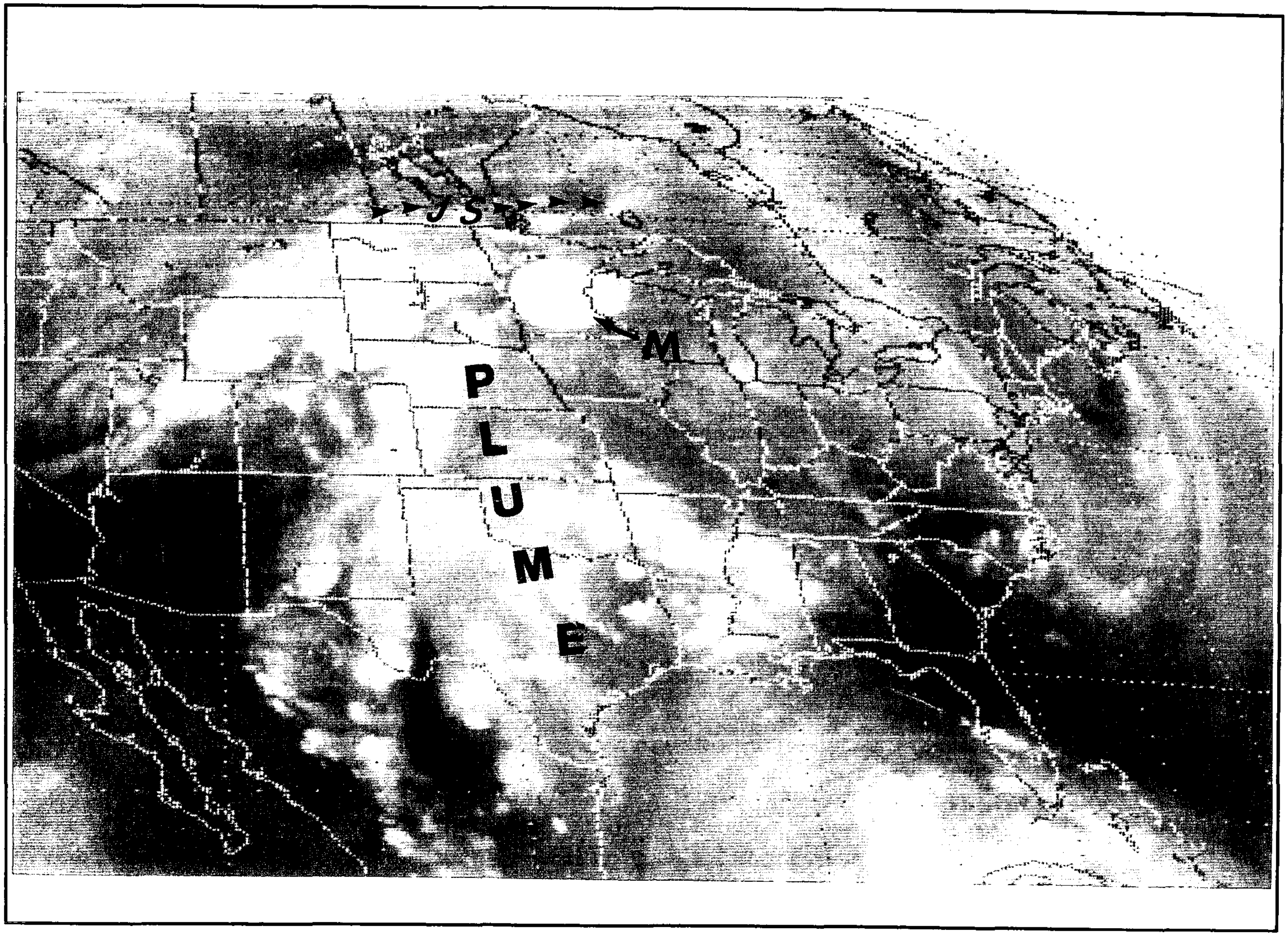


Figure C-2. *6.7μm water vapor imagery for 9 p.m. CDT, June 16, 1993 (02:00 UTC, June 17). Note water vapor plume (labeled PLUME on photo), Mesoscale Convective System (labeled M), and jet streak (labeled JS).*

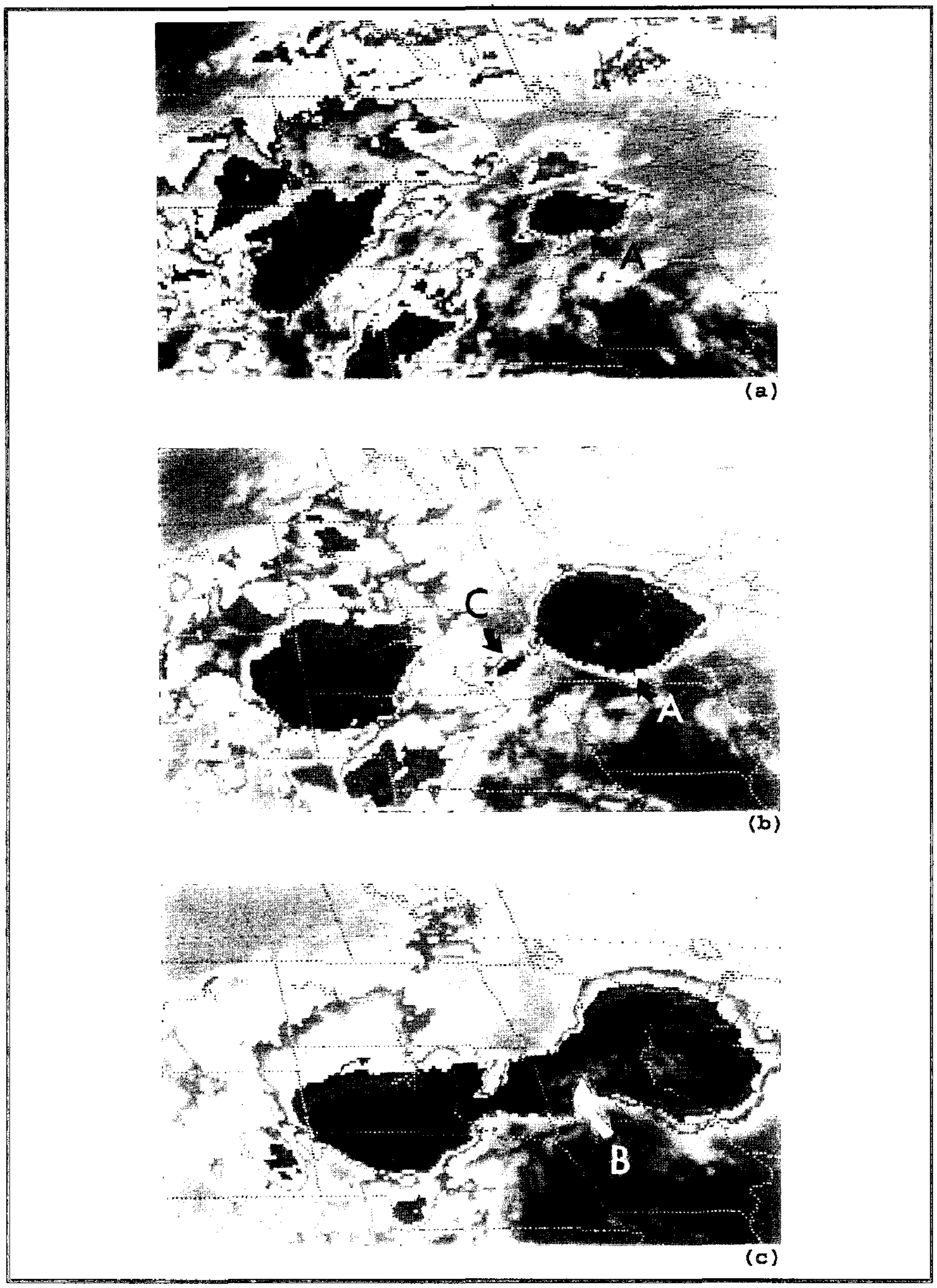


Figure C-3. *Enhanced infrared imagery (MB curve) during the evening hours of June 16, 1993: (a) 7:30 p.m. CDT (00:30 UTC, June 17), (b) 9:30 p.m. CDT (02:30 UTC, June 17), and (c) 11:30 p.m. CDT (04:30 UTC, June 17). Note growth and movement of one Mesoscale Convective System (MCS) (labeled A), development of a second MCS (labeled C), and merger of two MCSs (labeled B).*

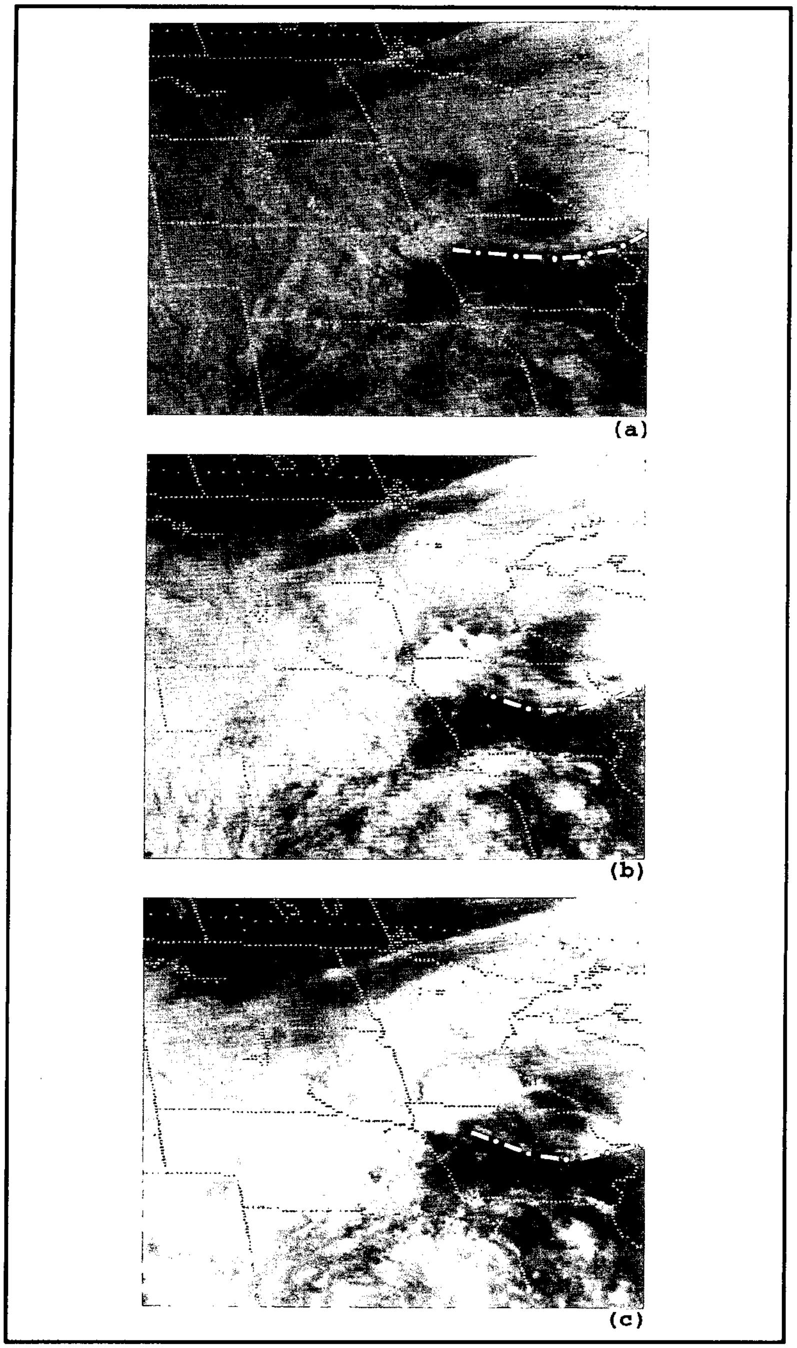


Figure C-4. *Visible imagery during the morning hours of June 17, 1993: (a) 9 a.m. CDT (14:00 UTC), (b) 10 a.m. CDT (15:00 UTC), and (c) 11 a.m. CDT (16:00 UTC). Note outflow boundaries (shown as dashed lines) produced by the previous evening's Mesoscale Convective System.*

gages that are not available in real-time. Therefore, these satellite estimates are useful as a "first guess" for determining the severity of a situation. Nevertheless, the estimates need to be validated and calibrated.

The SAB generated 38, 101, 206, and 95 satellite rainfall estimates for the Central Region in May, June, July, and August, respectively. May is included for comparison to show the period prior to the onset of the heaviest rains.

Satellite rainfall estimates are also passed on to the National Meteorological Center (NMC) meteorologists in the Heavy Precipitation Unit for input into their quantitative precipitation forecasts. The SAB has recently collocated with the Heavy Precipitation Unit to form the National Precipitation Prediction Unit (NPPU). During July and August, the NPPU provided the Federal Emergency Management Agency and the White House with daily briefings on the status of the heavy rains and flooding. The IFFA rainfall estimates and significant SPENES messages were included in these briefings.

Examples of an IFFA-derived graphic, text messages, and an analysis based on rain gage observations for a flash flood event over Missouri are shown in Figures C-5, C-6, and C-7, respectively. The IFFA graphic shows a large area of heavy rain from eastern Kansas to just west of St. Louis. Estimates ranged 5-8 inches over this area with a maxima of 8.5 inches in Bates County, Missouri (extreme western Missouri). The Satellite Precipitation Messages (SPENES) in Figure C-6 mention the presence of training and back-building MCSs over western Missouri and a 7-7.5 inch estimate over Bates County between 12:00-21:00 UTC. As mentioned above, back-building MCSs are frequently associated with flash floods. Rainfall observations in Figure C-7 were comparable to the IFFA estimates, except they were somewhat lower, especially over western Missouri. The Weather Surveillance Radar 1988 Doppler (WSR-88D) estimates (Figure C-8) show a local maximum just west of St. Louis of 8-9 inches of rain. Satellite estimates and rain gage observations indicate rainfall amounts of 7 inches near this same location.

In the spring of 1994, NOAA's next generation of geostationary satellites (GOES I-M) is scheduled for launch. The first satellite in that series in GOES I. The GOES I-M system promises to be a significant advancement in geostationary environmental satellite capabilities, especially for mesoscale prediction such as flash floods. All major portions of the system are new including: (1) improved multispectral imaging capability and (2) separate sounding and imaging systems. For application to flash flood diagnostics and prediction, the higher resolution IR (10.2-11.2 μm) and 6.7 μm water vapor data will lead to better detection of features that lead to heavy precipitation. Low-level water vapor can be diagnosed from the difference between the 11.2 μm and the 12.7 μm bands (the "split window"). Precipitable water, stability, and temperature can be derived from the satellite soundings. Winds at various levels can also be computed from the satellite data. GOES I in combination with the polar satellite data (discussed in the next section) places satellites at the very heart of understanding mesoscale weather development such as flash floods.

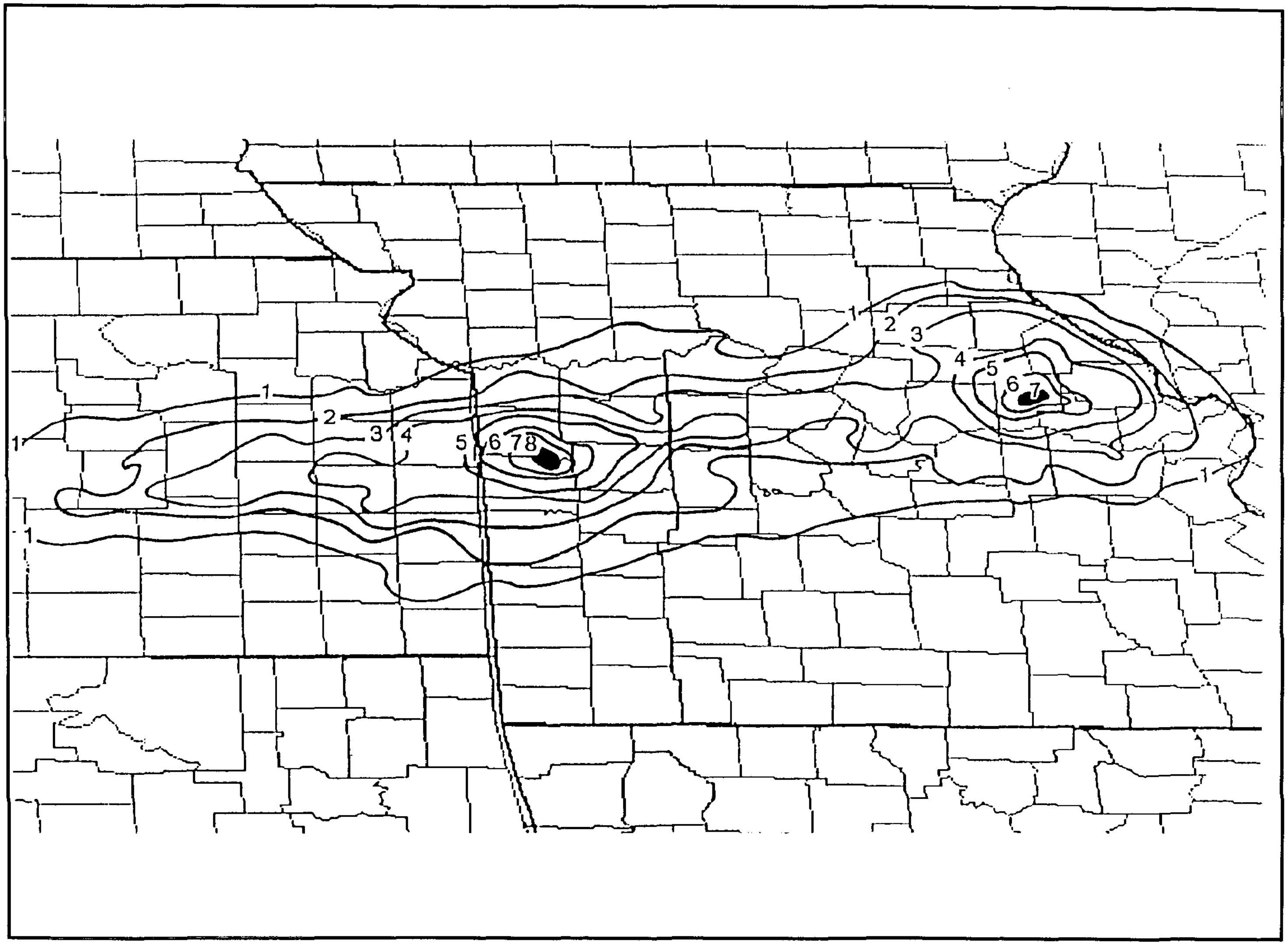


Figure C-5. *24-hour satellite-derived (IFFA) precipitation estimate for portions of central Kansas and central Missouri for the period ending at 7 a.m. CDT (12:00 UTC) on July 7, 1993.*

SATELLITE PRECIPITATION ESTIMATES... DATE/TIME/ 7/06/93 1935Z
PREPARED BY THE SYOPTIC ANALYSIS BRANCH/NESDIS TEL (301) 763-8444
VALUES REFLECT MAX OR SGFNT ESTS. OROGRAPHIC EFFECTS NOT ACCTD FOR.
REFER TO TPB*375 FOR DETAILS. LATEST DATA USED: 061900Z SJK

LOCATION	RATE	TOTAL	TIME
E. KS CNTYS...			
NE ALLEN/EXT NW BOURBON/SE ANDERSEN	1.0"	3.3"-3.8"	15-19Z
E LINN	1.0"	4.6" SE LINN	"
W CENTRAL MO...			
W/NW BATES	1.1"	5.0"-5.5" C BATES	"
C/SW CASS	1.0"	4.3" SE CASS	"
		3.5 S CENTRAL CASS	"

REMARKS...REDVLPMT ON BACK END OF MCS GIVING ADDTL HVYS RAIN TO E CENTRAL KS INTO W CENTRAL MO...TRAINING AND BACK BUILDING OVER E CENTRAL KS/ W CENTRAL MO...WILL MAKE FF POTNEITAL HIGH DURING THE NXT 3 HRS...WILL CONTINUE TO MONITOR WITH NXT MSG AFTER 21Z PIX...

SATELLITE PRECIPITATION ESTIMATES... DATE/TIME 7/06/93 2135Z
PREPARED BY THE SYOPTIC ANALYSIS BRANCH/NESDIS TEL. (301) 763-8444
VALUES REFLECT MAX OR SGFNT ESTS. OROGRAPHIC EFFECTS NOT ACCTD FOR.
REFER TO TPB*375 FOR DETAILS. LATEST DATA USED: 062100Z SJK

LOCATION	3 HR RATE	TOTALS	TIME
W CENTRAL MO...E KS	18-21Z		
W/SW CASS(MO)	3.0"	6.0"-6.5"EXT S/SW	12-21Z
EXT E MIAMI(KS)	2.6	5.0"-5.5"EXT SE MIAMI "	
NE LINN(KS)	1.5"	5.0"-5.5"	"
NW BATES (MO)	2.0"	7.0"-7.5" C BATES	
EXT S JACKSON TO SW JOHNSON(MO)	1.5"		
NW HENRY TO SW LAFAYETTE	1.6		
N BENTON TO MILLER TO S FRANKLIN(MO)		0.9"-1.2"	18-21Z

REMARKS...ONE LAST CONVECTIVE CELL SHUD TRAIN ACROSS SOUTHERN BACK PORTION ON AREA OF CONVECTION THAT HAS BEEN AFFECTING E KS/W CENTRAL MO PAST SEVERAL HRS...WILL BE MONITORING AREAS FROM JUST SW/SSE OF MKC THRU C MO TO S IL FOR HVY RAIN AND FF POTENTIAL OVER THE NXT 3 HRS...

Figure C-6. *Satellite precipitation messages for 2:35 p.m. CDT (19:35 UTC) and 4:35 p.m. CDT (21:35 UTC), July 6, 1993.*

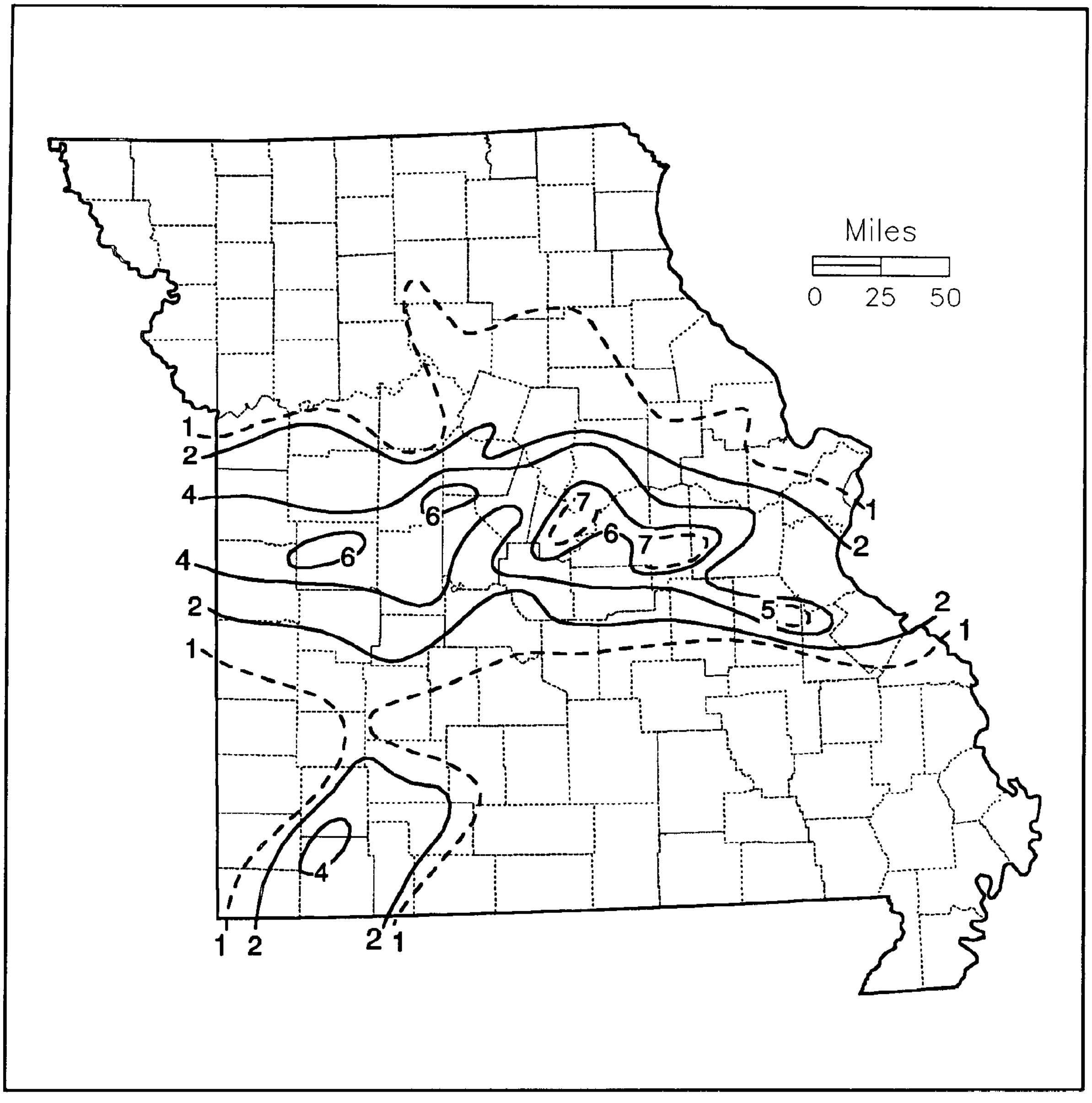


Figure C-7. *Analysis of total observed precipitation for the 24-hour period ending at 7 a.m. CDT (12:00 UTC) on July 7, 1993.*

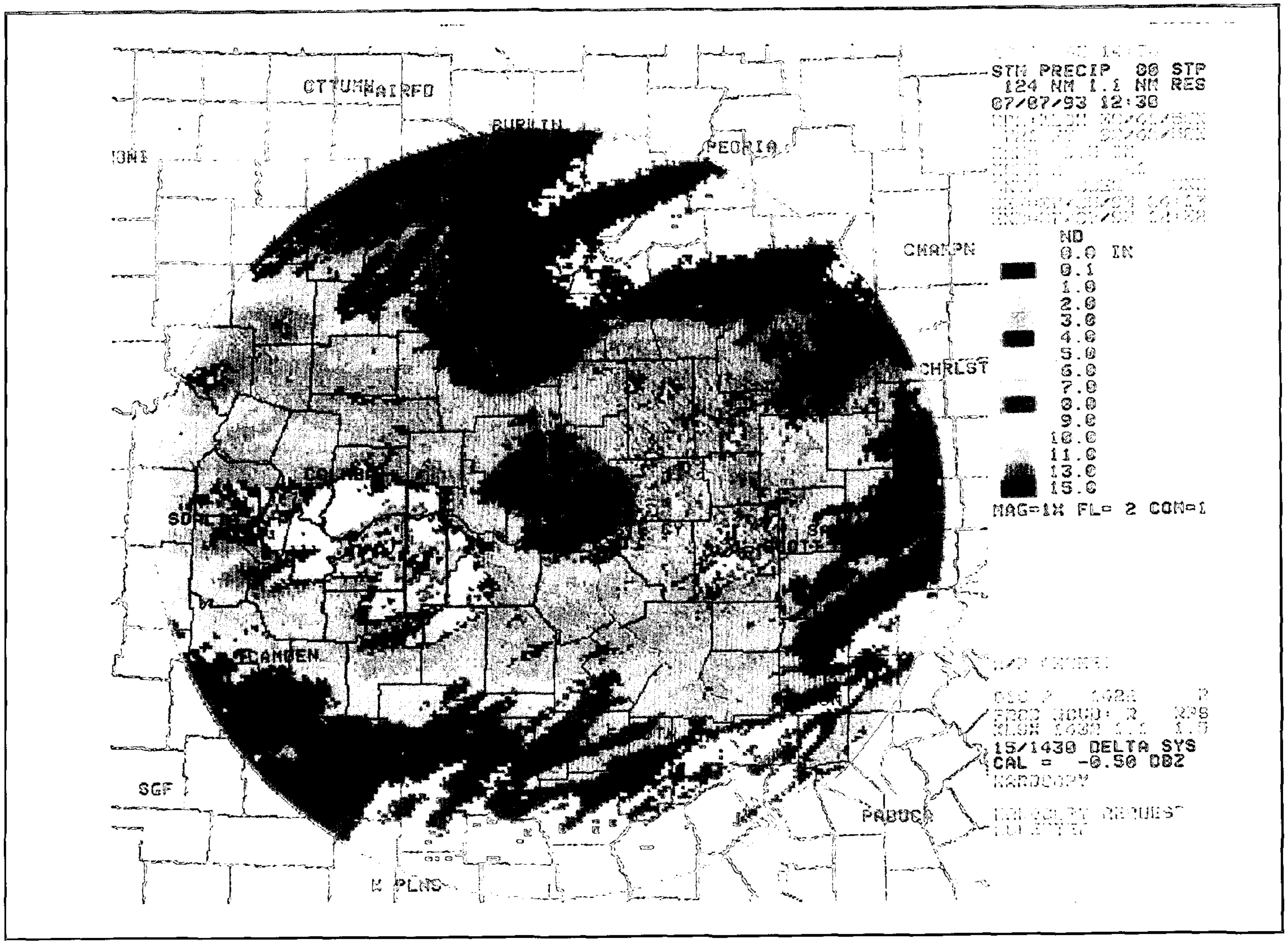


Figure C-8. *St. Louis, Missouri, WSR-88D image showing storm total precipitation ending at 7:32 a.m. CDT (12:32 UTC) on July 7, 1993.*

C.2. POLAR-ORBITING SATELLITE IMAGERY

The NOAA/NESDIS scientists used passive microwave data from the Defense Meteorological Satellite Program (DMSP) F-10 and F-11 series of polar-orbiting satellites to monitor the flooding in the Midwest.

Satellite imagery from polar-orbiting earth resource satellites, such as SPOT (France) and Landsat (USA), can be used to provide imagery of flood extent with spatial resolutions of 10 m and 30 m, respectively. Such high-resolution data are extremely useful in assessing the extent of damage caused by natural disasters. Corbley (1993) provides examples on the use of data from Landsat Thematic Mapper (TM) bands 7,4,3 for monitoring The Great Flood of 1993.

Thermal infrared data from the Advanced Very High Resolution Radiometer (AVHRR) instrument on board the NOAA-N series of satellites can also be used to examine flooding at spatial resolutions of up to 1.1 km. It is useful to compare images of the area of interest prior to and during the flood.

One of the key deficiencies of environmental satellites, such as the NOAA, Landsat, and SPOT series of satellites, is that they cannot see through clouds. The presence of clouds makes it very difficult to monitor land surface characteristics using visible (VIS) and thermal infrared (TIR) channel data. It is possible to overcome this limitation to some extent by compositing several images of the area of interest and selecting the relatively cloud-free pixels. However, in situations such as that in Iowa (where during the summer of 1993 it rained 40 out of 43 days), the applicability of VIS/TIR techniques for large area flood monitoring is somewhat limited by the requirement of relatively cloud-free days.

Clouds and ice crystals present in cirrus are "transparent" to radiation emanating from the earth in the microwave (MW) frequencies. The MW radiation still cannot penetrate rain. However, the MW techniques do provide better cloud and vegetation penetration than optical waves (Ulaby et al. 1981).

The Special Sensor Microwave/Imager (SSM/I) instrument on board the DMSP series of satellites measures passive MW radiation in seven frequencies: (1) 19.35 V (vertically polarized) GHz, (2) 19.35 H (horizontally polarized) GHz, (3) 22.235 V GHz, (4) 37.0 V GHz, (5) 37.0 H GHz, (6) 85.5 V GHz, and (7) 85 H GHz (Grody 1991).

Large bodies of water (such as lakes), as well as flooding following heavy rainfall events, lower the brightness temperatures at all MW frequencies. McFarland and Neale (1991) used a threshold of 4°K for the difference between the 22.235 V GHz and the 19.35 V GHz brightness temperatures to identify large bodies of water and flooding after heavy precipitation events. Scattering by clouds containing large water droplets and/or ice lowers the brightness temperature, particularly at the higher frequencies.

C.3 SOIL WETNESS INDEX

The experimental, NOAA-developed Soil Wetness Index uses the difference between the 85 GHz and 19 GHz horizontally polarized data from the SSM/I on board the DMSP satellites. The brightness temperature difference values in the range 10-30°K are then scaled between 0-255 and displayed. The experimental product is extremely useful for monitoring the areal extent of flooding under nearly all weather conditions, excluding actively precipitating cloud areas.

The Soil Wetness Index is used by NOAA to monitor soil wetness and flooding. Progressively wet ground conditions are depicted in shades of green, orange, and red, respectively (Figure C-9). Flooded or puddled land surfaces and large water bodies are shown in shades of blue. One can look for persistence of high soil wetness values in order to infer potential flooding conditions. Precipitation falling on already saturated soil can result in additional flooding. The images are composited with time to identify the flooded areas that may otherwise be obscured by precipitation.

The SSM/I channel data are readily available on a near real-time basis on the VDUC system located within the NOAA Science Center in Camp Springs, Maryland. The experimental Soil Wetness Index is being produced operationally on the VDUC system and is available in both digital and hard copy (color). SAB is already using it on an operational basis.

Figure C-9 shows the Soil Wetness Index for four different time periods. The June 6, 1993, imagery shows extremely wet to puddled soil conditions in southeastern Nebraska, much of Iowa and east-central Illinois. The flooding situation continued to persist in Iowa through June and late July. The flooding in Iowa reached a peak around July 15, 1993. The July 15 image also shows flooding in Kansas and along the Missouri River near St. Joseph, Kansas City, and Boonville. By July 20, surface waters were receding across farmlands in the Midwest. The Missouri and Mississippi Rivers and their tributaries continued to crest through August. The July 29 image shows flooded areas along the Missouri and Mississippi Rivers. Surface water detectable by the SSM/I sensors had largely disappeared in Iowa by this time.

The composite image of July 14, 1993, (Figure C-10) was used by Vice President Gore in a nationally televised press conference to illustrate the areal extent of the midwestern flooding. He said, "It is as if another Great Lake has been added to the map of the United States." Although the area is not really a lake, it does depict land surfaces that are either heavily puddled or almost submerged. Figure C-10 shows that large areas in Iowa, Illinois, Kansas, Missouri, Nebraska, Minnesota, and South Dakota were severely impacted by flooding at that time.

The Soil Wetness Index can also be used to monitor coastal and inland flooding due to hurricanes. The index was able to identify flooded areas in Florida after the passage of Hurricane Andrew.

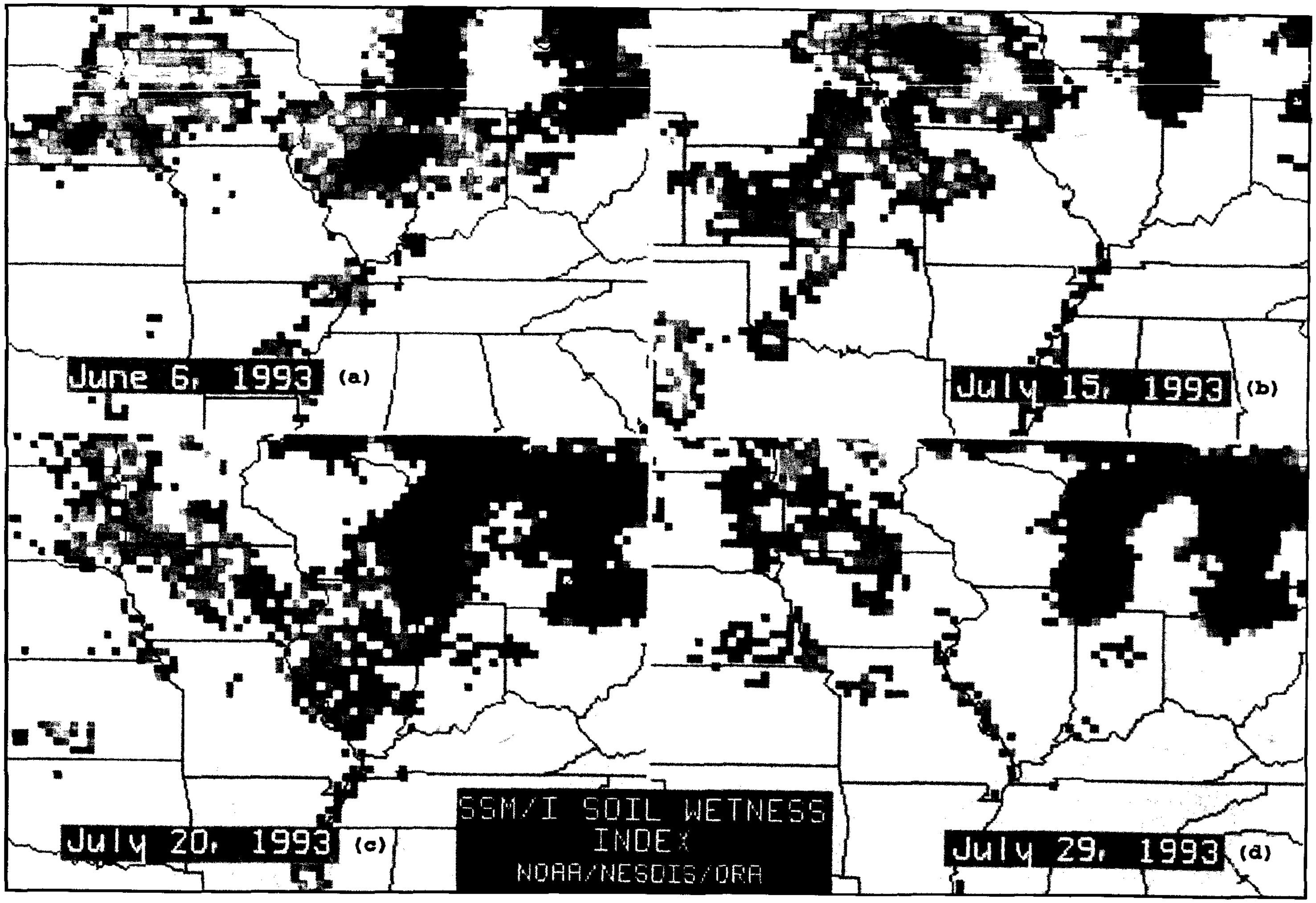


Figure C-9. *The SSM/I Soil Wetness Index for: (a) June 6, (b) July 15, (c) July 20, and (d) July 29, 1993.*

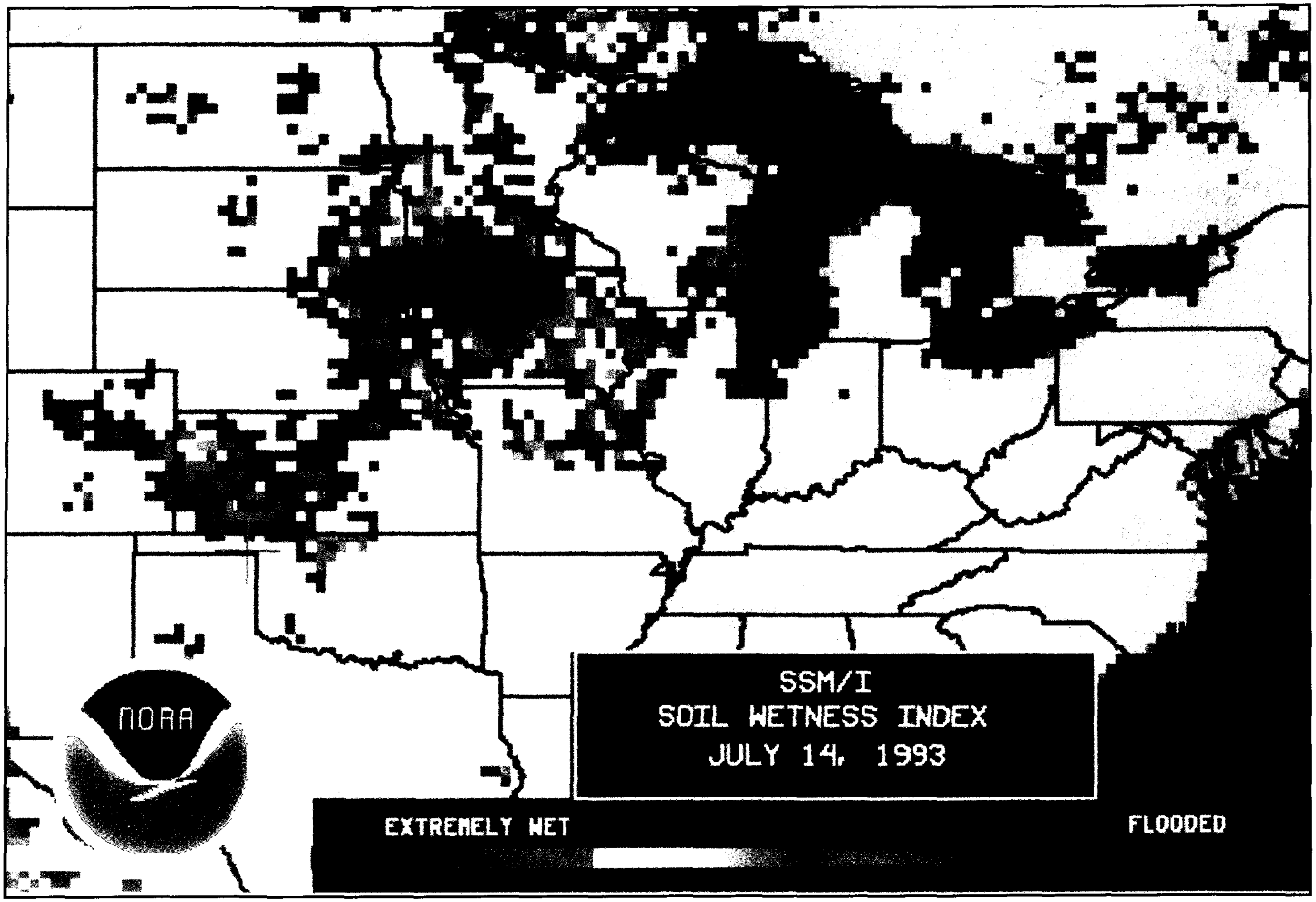


Figure C-10. *The SSM/I Soil Wetness Index for July 14, 1993.*

The Soil Wetness Index is an extremely useful tool for monitoring large area flooding. In its present form, the index values have been scaled to identify large geographic areas that are either extremely wet, puddled, or flooded. The puddled and flooded fields are indicated in various shades of blue. However, one has to look for persistence with time of these features in order to infer flooding.

C.4 SUGGESTIONS FOR FUTURE STUDY OF SATELLITE "IFFA-DERIVED" PRECIPITATION ESTIMATES

Additional research is needed to better use the satellite "IFFA-derived" precipitation estimates and the Soil Wetness Index. This will enhance our understanding of future hydrometeorological events. Listed below are suggestions for future studies for the satellite "IFFA-derived" precipitation estimates and for the Soil Wetness Index.

1. Since IFFA normally underestimates extreme rainfall, an objective correction factor must be derived that will automatically enhance the estimates during extreme rainfall events.

2. Validate and calibrate the estimates using doppler radar estimates and dense rain gage networks.

3. Integrate the estimates with the doppler radar estimates and rain gages.

4. Perform sensitivity studies to determine how to best insert the satellite estimates into hydrological models.

5. Use satellite estimates to help validate and initialize NMC's Numerical Weather Prediction Models.

C.5 SUGGESTIONS FOR FUTURE STUDY OF SOIL WETNESS INDEX

1. Archives of SSM/I channel data are available in-house within the Office of Research and Application for the period 1991 to present. It will be very useful to develop a climatology of the index over this period.

2. Compare the satellite-derived Soil Wetness Index with conventional indicators such as the Palmer Drought Index (PDI) and cumulative rainfall.

3. It may also be very useful to compare the Soil Wetness Index with the NOAA AVHRR channel data, especially the thermal channels.

4. Calibrate the index with ground-truth data (on field conditions) available weekly from the U.S. Department of Agriculture field offices in the impacted areas. The depth of flooding may be difficult to infer since the SSM/I instrument gets saturated even with the presence of a thin film of water on the surface. The index should be modified to flag desert areas.

5. Establish criteria for the proper interpretation of the index and develop a User's Manual for training purposes. The index could then be validated by the RFCs and other Weather Service Forecast Centers during the 1994 season.

6. Investigate procedures for integrating the Soil Wetness Index into hydrological models, such as over the Mississippi River basin.

C.6 REFERENCES

Borneman, R. 1988. Satellite rainfall estimating program of the NOAA/NESDIS Synoptic Analysis Branch. **Nat. Wea. Dig.**, 13, 2, 7-15.

Corbley, K.P. 1993. Remote sensing and GIS provide rapid response for flood relief. **Earth Observation Magazine**, September 1993, 28-31.

Grody, N. 1991. Classification of snow cover and precipitation using the Special Sensor Microwave/Imager. **Jour. of Geophys. Res.**, 96, 7423-7435.

McFarland, M.J., and C.M.U. Neale. 1991. Land parameter algorithm validation and calibration. In J.P. Hollinger (ed.), **DMSP Special Sensor Microwave/Imager Calibration/Validation**, Final Report, Volume II, 9-1 to 9-108. Naval Research Laboratory, Washington, DC.

Scofield, R.A. 1991. Satellite discussion of the Shadyside, Ohio flash flood event of June 14, 1990. Appendix D of the **Natural Disaster Survey Report Shadyside, Ohio, Flash Floods**, June 14, 1990. NOAA/NWS Report, U.S. Dept. of Commerce, Silver Spring, MD, D-1 to D-18.

Scofield, R.A. 1990b. The "water vapor imagery/theta-e connection" with heavy convective rainfall. **Proceedings of the EUMETSAT Workshop on NOWCASTING and Very Short Range Forecasting**, July 16-20, 1990, Shinfield Park, England, 173-178.

Scofield, R.A. 1987. The NESDIS operational convective precipitation estimation technique. **Mon. Wea. Rev.**, 115, 8, 1773-1792.

Scofield, R.A. and V.J. Oliver. 1977. A scheme for estimating convective rainfall from satellite imagery. **NOAA Tech. Memo**, NESS 86, U.S. Dept. of Commerce, Washington, DC, 47 pp.

Thiao, Wassila, R.A. Scofield, and J. Robinson. 1993. The relationship between water vapor plumes and extreme rainfall events during the summer season. **NOAA/NESDIS Technical Report 67**, U.S. Dept. of Commerce, Washington, DC, 69 pp.

Ulaby, F.T., R.K. Moore and A.K. Fung. 1981. In **Microwave Remote Sensing: Active and Passive**, Vol. I, pp 1-456. Addison-Wesley Pub, Company, Inc.

APPENDIX D

LOCATIONS WITH NEW RECORD AND NEAR-RECORD STAGES

Locations with new (preliminary) record stages in the upper Mississippi River basin (44 locations), the Missouri River basin (49 locations), and the Red River of the North basin (2 locations) are given in Tables D-1, D-2, and D-4, respectively. Locations that approach the flood of record in the Missouri River basin (24 locations) are given in Table D-3.

Table D-1. *Locations with new (preliminary) record stages in the upper Mississippi River basin.*

LOCATION Index Number		FLOOD STAGE (ft.)	OLD RECORD Stage (ft.)	OLD RECORD Date	PRELIMINARY NEW RECORD Stage (ft.)	PRELIMINARY NEW RECORD Date
Mississippi R						
1.	Quad Cities L/D15	15	22.5	650428	22.6	930709
2.	Muscatine IA	16	24.8	650429	25.6	930709
3.	Keithsburg IL	13	20.4	650427	24.2	930709
4.	Burlington IA	15	21.5	730425	25.1	930710
5.	Keokuk L/D19 IA	16	23.4	730424	27.2	930710
6.	Gregory Landing MO	15	24.6	730424	26.4	930707
7.	Quincy IL	17	28.9	730423	32.2	930713
8.	Hannibal MO	16	28.6	730425	31.8	930716
9.	Louisiana MO	15	27.0	730424	28.4	930728
10.	Clarksville MO L/D24	25	36.4	730424	37.7	930729
11.	Winfield MO L/D25	26	36.8	730427	39.6	930801
12.	Grafton IL	18	33.1	730428	38.2	930801
13.	Melvin Price IL	21	36.7	730428	42.7	930801
14.	St Louis MO	30	43.2	730428	49.58	930801
15.	Chester IL	27	43.3	730430	49.7	930807
Illinois R						
16.	Hardin IL	425	438.2	730429	442.3	930803
Rock R						
17.	Joslin IL	12	17.8	790322	18.4	930326
Spoon R						
18.	Seville IL	22	31.8	740624	33.1	930726
Squaw Creek						
19.	Ames IA	7	16.0	900617	18.5	930709
South Skunk R						
20.	Oskaloosa IA	15	23.1	900623	25.2	930715
21.	Squaw Creek IA	9	13.9	440520	14.2	930709

LOCATION Index Number	FLOOD STAGE (ft.)	OLD RECORD Stage (ft.)	OLD RECORD Date	PRELIMINARY NEW RECORD Stage (ft.)	PRELIMINARY NEW RECORD Date
Cedar R					
22. Conesville IA	12	16.9	900618	17.2	930406
English R					
23. Kalona IA	14	21.5	650921	22.6	930706
Beaver Creek					
24. New Hartford IA	8	13.5	470613	13.45	930331
Iowa R					
25. Marshalltown IA	13	20.5	900618	20.6	930709
26. Marengo IA	14	19.8	690712	20.3	930719
27. Lone Tree IA	15	20.3	650922	22.9	930707
28. Wapello IA	20	28.9	900619	29.5	930707
			RECORD FLOW		
E Fork Des Moines					
29. Algona IA	14	22.0	790823	22.65	930401
Raccoon R					
30. Van Meter IA	13	22.7	860701	25.8	930710
31. Des Moines SW18	12	19.8	470613	26.7	930711
North Raccoon R					
32. Perry IA	13	22.7	790320	23.0	930710
Des Moines R					
33. Des Moines 2ND AV	23	30.2	540624	31.7	930711
34. Des Moines SE 14TH	23	29.8	650411	34.3	930711
35. Ottumwa IA	10	21.0	470607	22.1	930712
36. Keosauqua IA	25	29.4	650411	32.7	930713
37. St Francisville MO	18	30.2	790314	32.0	930715
Baraboo R					
38. Baraboo WI	16	20.7	920920	22.8	930718
Black R					
39. Galesville WI	12	15.5	800923	16.6	930621

LOCATION Index Number	FLOOD STAGE (ft.)	OLD RECORD Stage (ft.)	OLD RECORD Date	PRELIMINARY NEW RECORD Stage (ft.)	PRELIMINARY NEW RECORD Date
Pecatonica R					
40. Blanchardville WI	19	21.5	480228	22.0	930706
Little Minnesota R					
41. Peever SD	11	13.4	430325	13.6	930727
Minnesota R					
42. Mankato MN	19	29.1	650415	30.1	930621
Redwood R					
43. Marshall MN	14	15.6	690419	17.0	930509
Meramec R					
44. Arnold MO	24	43.9	821206	45.3	930801

Table D-2. *Locations with new (preliminary) record stages in the Missouri basin.*

LOCATION Index Number	FLOOD STAGE (ft.)	OLD RECORD Stage (ft.)	OLD RECORD Date	PRELIMINARY NEW RECORD Stage (ft.)	PRELIMINARY NEW RECORD Date
Pipestem Creek					
45. Pipestem Res ND	1496.3	1468.35	790510	1472.0	930804
James R					
46. Mitchell SD	14	18.3	690411	19.1	930704
Weeping Water Creek					
47. Union NE	25	29.8	580509	31.2	930723
Wood R					
48. Grand Island NE	4.8	6.0	670616	6.4	930722
Salt Creek					
49. Greenwood NE	20	26.5	840613	26.5	930724
50. Ashland NE	16	22.0	840613	23.0	930723
W Nishnabotna R					
51. Hancock IA	14	22.1	720913	23.53	930710
Nishnabotna R					
52. Hamburg IA	16	28.1	870527	30.52	930725
Rock R					
53. Rock Rapids IA	6	10.2	690408	12.5	930509
Nodaway R					
54. Graham MO	N/A	20.4	840615	26.1	930723
102 R					
55. Bedford IA	21	23.5	860714	23.79	930705
56. Maryville MO	14	19.3	731012	20.3	930706
Platte R					
57. Sharps Station MO	23	34.6	840610	36.4	930726
58. Agency MO	20	35.1	650720	36.0	930725

LOCATION Index Number	FLOOD STAGE (ft.)	OLD RECORD Stage (ft.)	OLD RECORD Date	PRELIMINARY NEW RECORD Stage (ft.)	PRELIMINARY NEW RECORD Date
South Fork Solomon R					
59. Osborne KS	14	27.7	510713	28.5	930721
60. Waconda Res KS	1488.3	1471.3	870427	1487.0	930728
Saline R					
61. Russell KS	18	19.7	640901	25.4	930721
62. Wilson Res KS	1554	1528.1	930426	1547.9	930801
63. Lincoln KS	30	34.7	580519	37.8	930722
64. Tescott KS	25	30.1	510713	30.8	930723
Big Creek					
65. Munjor KS	18	N/A		26.2	930721
Smoky Hill R					
66. Abilene KS	27	N/A		32.1	930722
67. Enterprise KS	26	34.0	510713	34.2	930723
68. Junction City KS	22	N/A		29.6	930722
Delaware R					
69. Perry Res KS	920.6	917.07	731019	920.9	930725
Big Blue R					
70. Blue Rapids KS	26	53.1	731018	63.3	930723
71. Tuttle Creek Res KS	1136	1127.9	731018	1137.76	930722
Fancy Creek					
72. Randolph KS	11	26.5	731018	36.3	930722
Black Vermillion					
73. Frankfort KS	19	30.1	731011	32.2	930722
Republican R					
74. Milford KS	1176.2	1170.03	731017	1181.85	930725

LOCATION Index Number	FLOOD STAGE (ft.)	OLD RECORD Stage (ft.)	OLD RECORD Date	PRELIMINARY NEW RECORD Stage (ft.)	PRELIMINARY NEW RECORD Date
Grand R					
75. Pattonsburg MO	25	34.3	470600	37.6	930724
76. Chillicothe MO	24	34.7	910500	38.5	930709
77. Sumner MO	26	39.5	470607	42.6	930710
78. Brunswick MO	16	26.1	510717	31.7	930713
	HWY 24 OBS Downtown Gage			37.7	
Chariton R					
79. Rathbun Res IA	926	924.46	820722	927.2	930728
Missouri R					
80. Plattsmouth NE	26	34.66	840614	35.7	930725
81. Brownville NE	32	41.2	840615	44.3	930724
82. St. Joseph MO	17	26.8	520422	32.69	930726
83. Kansas City MO	32	46.2	510714	48.9	930728
84. Napoleon MO	17	26.8	510715	27.76	930727
85. Lexington MO	22	33.3	510715	33.4	930708
86. Waverly MO	20	29.2	840623	31.2	930728
87. Miami MO	18	29.0	510716	32.4	930729
88. Glasgow MO	25	36.7	510718	39.6	930729
89. Boonville MO	21	32.8	510717	37.1	930729
90. Jefferson City MO	23	34.2	510718	38.6	930730
91. Gasconade MO	22	38.7	861005	39.6	930731
92. Hermann MO	21	35.8	561005	36.3	930731
93. St. Charles MO	25	37.5	861007	39.5	930801

Table D-3. *Locations with near-record stages in the Missouri basin.*

LOCATION Index Number	FLOOD STAGE (ft.)	OLD RECORD Stage (ft.)	OLD RECORD Date	PRELIMINARY 1993 STAGE Stage (ft.)	PRELIMINARY 1993 STAGE Date
James R					
94. Jamestown Res ND	1454	1444.1	690427	1440.0	930804
Vermillion R					
95. Davis SD	11	15.8	690405	15.6	930705
Ponca Creek					
96. Verdel NE	12	15.6	600327	14.0	930714
Big Sioux R					
97. Hawarden IA	15	24.6	690409	24.3	930712
98. Akron IA	16	23.0	690409	22.6	930713
Soldier R					
99. Pisgah IA	28	28.2	500612	27.58	930710
			RECORD FLOW		
Wood R					
100. Alda NE	10	12.2	670616	11.2	930727
Shell Creek					
101. Columbus NE	20	22.8	900617	21.5	930710
Platte R					
102. Louisville NE	9	12.5	930330	12.0	930724
Tarkio R					
103. Fairfax MO	17	25.9	820800	25.7	930723
Platte R					
104. Platte City MO	18	37.8	650720	32.0	930726
Solomon R					
105. Minneapolis KS	26	34.1	510713	32.4	930721
106. Niles KS	24	31.8	510714	30.2	930722

LOCATION Index Number	FLOOD STAGE (ft.)	OLD RECORD Stage (ft.)	 Date	PRELIMINARY 1993 STAGE Stage (ft.)	 Date
Salt Creek					
107. Ada KS	18	23.3	610523	22.3	930719
Smoky Hill R					
108. Ellsworth KS	20	27.2	380601	26.1	930723
109. Kanopolis Res KS	1508	1506.98	510714	1505.7	930726
110. New Cambria KS	27	32.4	731012	31.6	930722
Republican R					
111. Clay Center KS	15	25.7	350603	23.4	930724
Mulberry Creek					
112. Salina KS	24	27.4	730926	26.4	930722
South Grand R					
113. Urich MO	22	27.9	850223	27.1	930707
Missouri R					
114. Nebraska City NE	18	27.7	520418	27.16	930723
115. Rulo NE	17	25.6	520422	25.24	930724
116. Sibley MO	22	35.6	510715	34.6	930729

Table D-4. *Locations with new (preliminary) record stages in the Red River of the North basin.*

LOCATION Index Number	FLOOD STAGE (ft.)	OLD RECORD Stage (ft.)	 Date	PRELIMINARY NEW RECORD Stage (ft.)	 Date
Buffalo R					
117. Hawley MN	7	9.8	750701	10.9	930718
Two Rivers					
118. Hallock MN	802	807.5	850627	808.1	930815
		810.2	660406 HIGH WATER MARK PRIOR TO GAGE INSTALLATION		

APPENDIX E

WEATHER SERVICE FORECAST OFFICE PRODUCT ISSUANCE SUMMARY

The Great Flood of 1993 began in the early spring and continued into the fall of 1993 across the Upper Midwest. Record flooding occurred at several forecast points in April and May. Nonetheless, the vast majority of the devastating flooding occurred during June, July, and early August. A primary goal of this disaster survey report is to assess the quality of services provided by the National Weather Service during the peak flooding period. Consequently, a summary of the Weather Service Forecast Office products, by week, from June through mid-August is given in this appendix. The intent is to convey the order of magnitude of the various weather and flood forecast products issued by the NWS field offices during the period of the most disastrous and intense flooding.

PRODUCT ISSUANCE SUMMARY

WSFO BISMARCK

WEEK	FLW	FLS	RVA	RVS	FFA	FFW	FFS	SVR	TOR	SVS	SPS
06/01-06/05	0	2	0	0	0	0	0	0	0	0	1
06/06-06/12	0	0	0	0	0	0	0	9	0	14	24
06/13-06/19	0	2	0	0	0	0	0	0	0	0	9
06/20-06/26	0	1	0	0	0	0	1	13	3	19	23
06/27-07/03	0	1	0	0	0	0	1	9	5	14	39
07/04-07/10	0	0	0	0	0	0	0	2	0	4	27
07/11-07/17	2	5	0	0	5	6	27	11	0	1	27
07/18-07/24	1	14	0	0	8	5	23	9	3	15	39
07/25-07/31	1	12	0	0	5	0	13	0	1	2	7
08/01-08/07	0	13	0	0	0	0	0	0	0	0	2
08/08-08/14	0	5	0	0	1	0	1	8	0	5	28
TOTALS	4	55	0	0	19	11	66	61	12	74	226

WSFO CHICAGO

WEEK	FLW	FLS	RVA	RVS	FFA	FFW	FFS	SVR	TOR	SVS	SPS
06/01-06/05	0	0	15	0	0	0	0	0	0	*	*
06/06-06/12	1	38	21	0	5	1	4	21	3	*	*
06/13-06/19	0	30	21	0	4	0	3	8	0	*	*
06/20-06/26	3	35	21	0	1	0	2	3	1	*	*
06/27-07/03	3	39	21	0	2	2	9	23	0	*	*
07/04-07/10	1	39	21	0	2	3	7	2	0	*	*
07/11-07/17	1	34	21	0	6	2	5	0	0	*	*
07/18-07/24	1	45	21	0	0	5	6	2	0	*	*
07/25-07/31	0	43	21	0	0	0	1	0	0	*	*
08/01-08/07	0	23	21	0	0	0	0	3	0	*	*
08/08-08/14	0	24	21	0	0	2	4	0	0	*	*
TOTALS	7	345	225	0	20	15	41	62	4	*	*

FLW-FLOOD WARNING
FLS-FLOOD STATEMENT
RVA-RIVER SUMMARY
RVS-RIVER STATEMENT
FFA-FLASH FLOOD WATCH
FFW-FLASH FLOOD WARNING
FFS-FLASH FLOOD STATEMENT
SVR-SEVERE THUNDERSTORM WARNING
TOR-TORNADO WARNING
SVS-SEVERE WEATHER STATEMENT
SPS-SPECIAL WEATHER STATEMENT
"*" Denotes data unavailable

PRODUCT ISSUANCE SUMMARY

WSFO DES MOINES

WEEK	FLW	FLS	RVA	RVS	FFA	FFW	FFS	SVR	TOR	SVS	SPS
06/01-06/05	0	4	1	0	0	0	0	0	0	0	0
06/06-06/12	0	46	4	0	7	7	23	21	0	26	86
06/13-06/19	4	42	6	4	3	4	16	19	0	24	72
06/20-06/26	0	41	8	0	2	6	13	4	0	4	32
06/27-07/03	1	36	9	3	9	16	33	16	0	18	72
07/04-07/10	11	88	11	0	4	12	30	16	4	23	78
07/11-07/17	7	34	2	0	5	14	30	2	0	3	74
07/18-07/24	0	26	7	0	11	5	19	0	0	0	82
07/25-07/31	0	30	9	1	0	5	22	20	0	34	45
08/01-08/07	0	31	13	0	0	0	0	0	0	0	4
08/08-08/14	1	16	7	0	2	3	21	12	0	10	54
TOTALS	24	394	77	8	43	72	207	110	4	142	599

WSFO MINNEAPOLIS

WEEK	FLW	FLS	RVA	RVS	FFA	FFW	FFS	SVR	TOR	SVS	SPS
06/01 - 06/05	0	6	5	0	0	0	0	0	0	0	0
06/06 - 06/12	0	9	7	0	0	0	0	2	5	9	19
06/13 - 06/19	2	28	8	0	4	1	4	0	0	0	7
06/20 - 06/26	6	27	9	0	5	0	7	0	0	0	10
06/27 - 07/03	2	11	7	0	4	0	4	2	0	7	16
07/04 - 07/10	0	9	10	0	3	0	3	2	1	3	5
07/11 - 07/17	0	7	7	0	2	0	2	0	0	0	1
07/18 - 07/24	0	7	7	0	4	0	2	1	1	2	1
07/25 - 07/31	0	8	7	0	6	0	5	4	1	9	8
08/01 - 08/07	0	6	6	0	0	0	0	0	0	0	0
08/08 - 08/14	0	6	7	0	2	0	0	2	0	2	4
TOTALS	10	124	80	0	30	1	27	13	8	32	71

FLW-FLOOD WARNING
FLS-FLOOD STATEMENT
RVA-RIVER SUMMARY
RVS-RIVER STATEMENT
FFA-FLASH FLOOD WATCH
FFW-FLASH FLOOD WARNING
FFS-FLASH FLOOD STATEMENT
SVR-SEVERE THUNDERSTORM WARNING
TOR-TORNADO WARNING
SVS-SEVERE WEATHER STATEMENT
SPS-SPECIAL WEATHER STATEMENT

PRODUCT ISSUANCE SUMMARY

WSFO MILWAUKEE

WEEK	FLW	FLS	RVA	RVS	FFA	FFW	FFS	SVR	TOR	SVS	SPS
06/01 - 06/05	0	1	5	1	0	0	0	0	0	0	4
06/06 - 06/12	0	12	7	8	0	0	0	15	8	51	39
06/13 - 06/19	3	12	7	10	3	3	9	11	1	30	34
06/20 - 06/26	8	35	7	2	1	0	2	4	2	15	20
06/27 - 07/03	5	16	7	3	0	0	0	7	1	20	26
07/04 - 07/10	8	28	7	5	1	1	1	17	1	45	37
07/11 - 07/17	1	35	7	2	2	0	0	0	0	0	5
07/18 - 07/24	1	21	7	0	4	0	4	0	0	0	7
07/25 - 07/31	1	21	7	3	0	0	0	7	1	21	25
08/01 - 08/07	0	12	7	1	0	0	0	0	0	0	6
08/08 - 08/14	0	9	7	1	0	0	0	0	0	0	5
TOTALS	27	202	75	36	11	4	16	61	14	182	208

WSFO OMAHA

WEEK	FLW	FLS	RVA	RVS	FFA	FFW	FFS	SVR	TOR	SVS	SPS
06/01 - 06/05	0	0	0	0	0	0	0	0	0	0	8
06/06 - 06/12	0	1	0	0	2	0	5	2	0	2	28
06/13 - 06/19	1	1	0	2	2	1	8	4	0	2	15
06/20 - 06/26	0	4	0	1	0	0	1	5	1	7	14
06/27 - 07/03	5	16	0	0	0	3	10	8	3	8	35
07/04 - 07/10	7	27	0	0	6	1	12	4	3	2	28
07/11 - 07/17	15	24	0	0	8	4	23	2	0	2	24
07/18 - 07/24	19	35	0	0	13	8	28	0	5	5	31
07/25 - 07/31	8	61	0	1	2	0	6	3	0	4	15
08/01 - 08/07	0	1	0	0	0	0	0	0	0	0	2
08/08 - 08/14	0	0	0	0	0	1	2	4	2	6	13
TOTALS	55	170	0	4	33	18	95	32	14	38	213

FLW-FLOOD WARNING
FLS-FLOOD STATEMENT
RVA-RIVER SUMMARY
RVS-RIVER STATEMENT
FFA-FLASH FLOOD WATCH
FFW-FLASH FLOOD WARNING
FFS-FLASH FLOOD STATEMENT
SVR-SEVERE THUNDERSTORM WARNING
TOR-TORNADO WARNING
SVS-SEVERE WEATHER STATEMENT
SPS-SPECIAL WEATHER STATEMENT

PRODUCT ISSUANCE SUMMARY

WSFO SAINT LOUIS

WEEK	FLW	FLS	RVA	RVS	FFA	FFW	FFS	SVR	TOR	SVS	SPS
06/01 - 06/05	3	8	30	5	2	0	2	0	0	0	0
06/06 - 06/12	9	34	42	12	2	3	18	13	1	13	36
06/13 - 06/19	9	24	50	10	2	3	3	3	0	5	20
06/20 - 06/26	6	35	48	8	3	4	14	3	0	2	24
06/27 - 07/03	16	56	42	19	11	16	24	34	5	56	43
07/04 - 07/10	13	116	42	29	24	61	116	10	0	10	43
07/11 - 07/17	7	107	42	21	20	10	66	4	0	7	16
07/18 - 07/24	13	124	50	11	10	7	28	14	1	25	36
07/25 - 07/31	2	113	48	5	6	3	15	13	3	12	42
08/01 - 08/07	0	85	42	0	0	3	8	13	3	12	42
08/08 - 08/14	8	54	42	7	4	6	22	1	0	2	10
TOTALS	86	756	478	127	84	116	316	108	13	144	312

WSFO SIOUX FALLS

WEEK	FLW	FLS	RVA	RVS	FFA	FFW	FFS	SVR	TOR	SVS	SPS
06/01 - 06/05	0	7	0	0	0	0	0	0	0	0	0
06/06 - 06/12	0	7	0	1	3	0	2	9	5	7	12
06/13 - 06/19	2	7	0	0	2	3	4	9	0	7	17
06/20 - 06/26	1	9	0	0	2	0	1	6	0	7	12
06/27 - 07/03	2	8	0	0	3	11	7	61	5	37	37
07/04 - 07/10	0	10	0	0	1	3	1	11	2	8	17
07/11 - 07/17	0	22	0	0	2	0	6	1	0	1	15
07/18 - 07/24	0	7	0	0	3	0	3	9	2	11	8
07/25 - 07/31	3	7	0	0	1	1	5	7	0	6	6
08/01 - 08/07	0	7	0	0	0	0	0	0	0	0	0
08/08 - 08/14	0	7	0	0	0	1	1	1	0	2	2
TOTALS	8	98	0	1	17	19	30	114	14	86	126

FLW-FLOOD WARNING
FLS-FLOOD STATEMENT
RVA-RIVER SUMMARY
RVS-RIVER STATEMENT
FFA-FLASH FLOOD WATCH
FFW-FLASH FLOOD WARNING
FFS-FLASH FLOOD STATEMENT
SVR-SEVERE THUNDERSTORM WARNING
TOR-TORNADO WARNING
SVS-SEVERE WEATHER STATEMENT
SPS-SPECIAL WEATHER STATEMENT

PRODUCT ISSUANCE SUMMARY

WSFO TOPEKA

WEEK	FLW	FLS	RVA	RVS	FFA	FFW	FFS	SVR	TOR	SVS	SPS
06/01 - 06/05	0	2	0	0	0	0	0	0	0	0	29
06/06 - 06/12	0	0	0	0	0	0	0	13	0	23	60
06/13 - 06/19	0	2	4	7	2	0	4	6	2	12	36
06/20 - 06/26	0	23	3	18	2	0	4	0	0	0	53
06/27 - 07/03	4	18	4	5	5	5	20	14	9	29	69
07/04 - 07/10	1	65	4	5	12	10	40	21	5	49	85
07/11 - 07/17	4	83	7	6	5	1	7	0	0	0	45
07/18 - 07/24	4	141	5	3	11	14	36	9	2	15	55
07/25 - 07/31	1	56	7	0	2	4	13	3	0	7	32
08/01 - 08/07	0	23	4	2	0	0	0	0	0	0	4
08/08 - 08/14	0	5	4	2	0	0	0	1	0	2	29
TOTALS	14	418	42	48	39	34	124	67	18	137	497

FLW-FLOOD WARNING
FLS-FLOOD STATEMENT
RVA-RIVER SUMMARY
RVS-RIVER STATEMENT
FFA-FLASH FLOOD WATCH
FFW-FLASH FLOOD WARNING
FFS-FLASH FLOOD STATEMENT
SVR-SEVERE THUNDERSTORM WARNING
TOR-TORNADO WARNING
SVS-SEVERE WEATHER STATEMENT
SPS-SPECIAL WEATHER STATEMENT

APPENDIX F

ANALYSIS OF SELECTED HYDROLOGIC FORECASTS

This appendix is closely linked with Chapter 6, and especially with Sections 6.4 and 6.5, which discuss hydrologic services for both the upper Mississippi and the Missouri River basins. Both the North Central River Forecast Center (NCRFC) and the Missouri Basin River Forecast Center (MBRFC) make routine hydrologic forecasts for numerous points along the main stems of the Mississippi and Missouri Rivers, respectively. The NCRFC has 27 such forecast points, while the MBRFC has 18. At a few forecast points, long-term forecasts of river stages are generated that range from 7 to as many as 28 days into the future. It is possible to evaluate the skill of these long-range forecasts by comparing the forecast river stages with the observed river stages.

This appendix examines long-range forecasts issued by both the NCRFC and the MBRFC for two points along the main stem Mississippi River (St. Louis, Missouri, and Chester, Illinois) and for three points along the main stem Missouri River (Sioux City, Iowa; Boonville, Missouri; and Hermann, Missouri), respectively. Both River Forecast Centers (RFC) provided the disaster survey team with forecast and observed data for each forecast point for the period June-August 1993. A series of hydrographs (some of which appear in Chapter 6, Figures 6-6 and 6-7) were then generated for each of these five forecast points for lead-times out to 28 days for all forecast points except Sioux City, Iowa, which has a lead-time only out to 7 days. These hydrographs appear in Figures F-1 through F-13 following this discussion.

For example, the top panel (a) in Figure F-1 shows the observed stages (solid line) and 1-day forecast stages (x symbol) for each day during June-August 1993 at the St. Louis, Missouri, forecast point along the Mississippi River. The forecast stages plotted were actually generated 1 day earlier than the date which is shown, i.e., the forecast stage plotted for June 2 was generated and released by the NCRFC 1 day earlier, on June 1. Similarly, the middle panel (b) in Figure F-1 shows the observed stages again (solid line; note that this line is the same on each graph, as it represents observed river stages) and the 3-day forecast stages. On this graph, the forecast stages plotted were actually generated 3 days earlier than the date indicated, i.e., the forecast stage plotted for June 4 was generated and released by the NCRFC 3 days earlier, on June 1. All other graphs in this appendix are plotted in the same manner. Note that at longer forecast ranges, i.e., beyond 7-day forecasts, the forecasts are not generated by the RFC on a daily basis (see Figure F-2, top panel (a)). Also, plotted on each graph are the flood stage and the previous record flood stage.

A degradation in skill is expected as forecast lead-times extend into the future. In other words, forecasts are typically better at shorter time ranges than at longer time ranges. A principal reason for the decreased skill with increasing lead-time is associated with the fact that precipitation that falls after the long-term forecast has been generated is never accounted for. Consequently, hydrologic forecasts tend to "underforecast," especially if significant precipitation falls in the drainage area of the forecast point after the forecast has been made. A systematic underestimate (or overestimate) is referred to as bias. The longer-duration forecasts clearly show a systematic underestimate, or bias. Generally, the bias increases with increasing forecast lead-times.

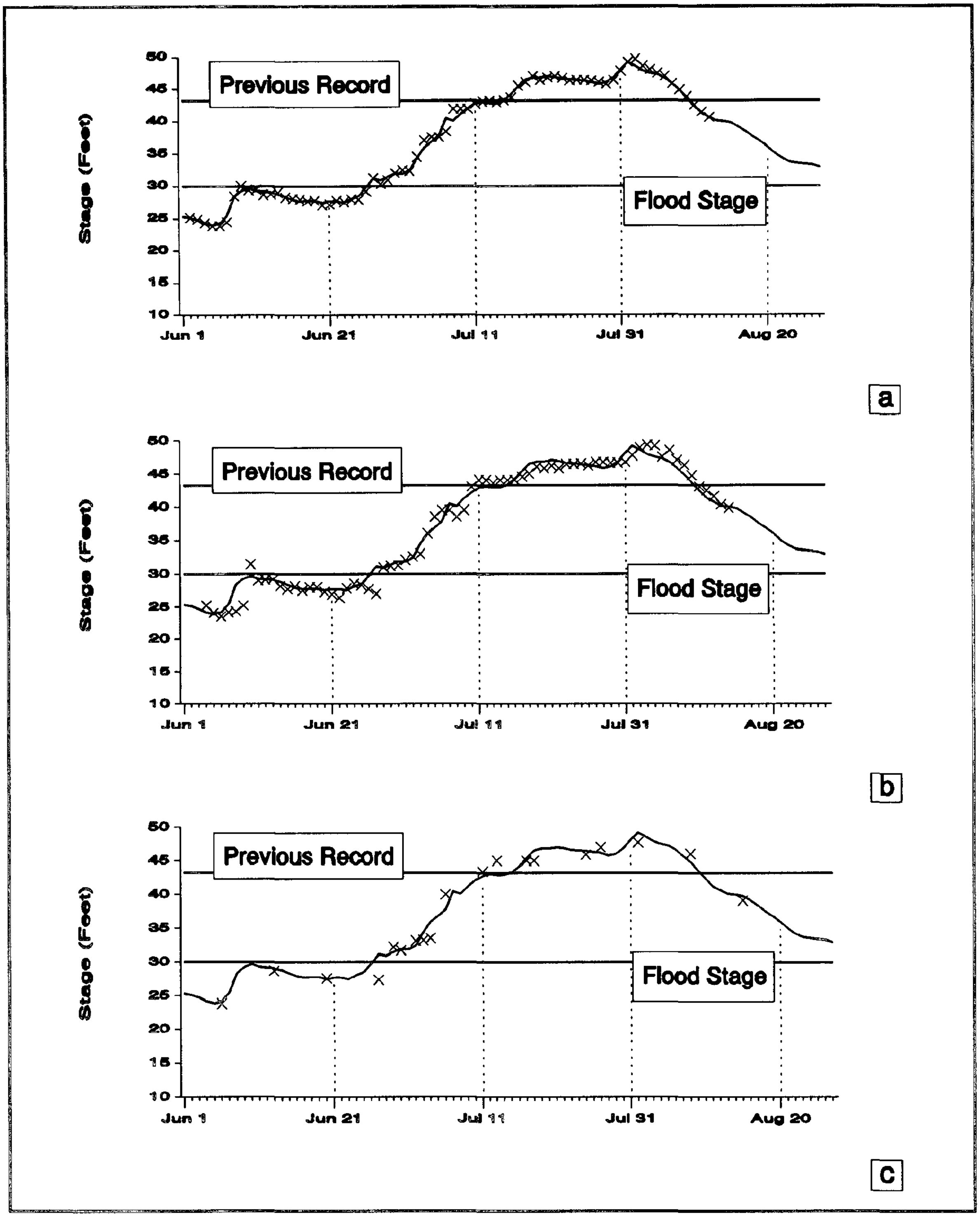


Figure F-1. *Forecast (x) and observed (solid lines) river stages along the Mississippi River at St. Louis, Missouri: (a) 1-day forecasts, (b) 3-day forecasts, and (c) 5-day forecasts.*

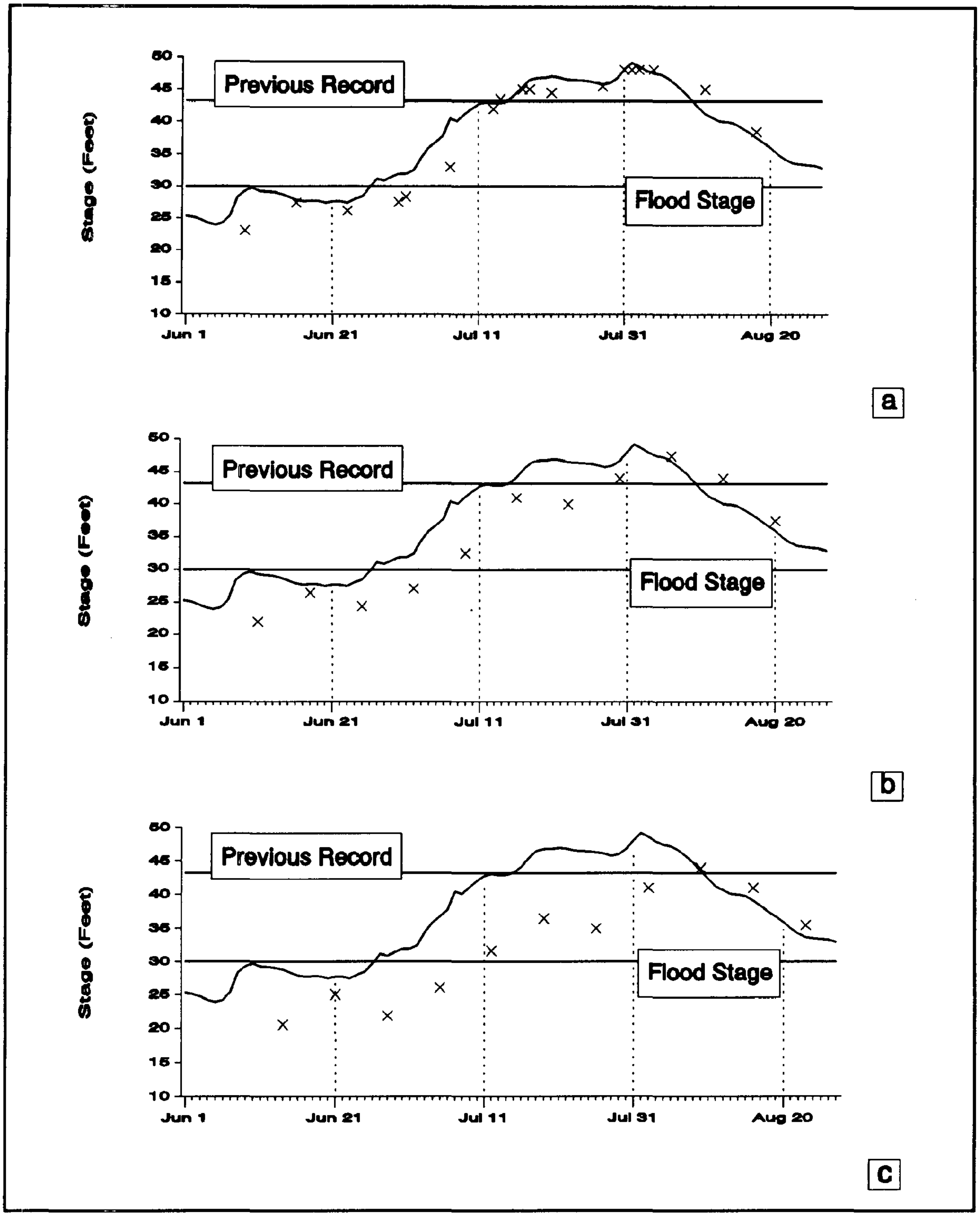


Figure F-2. *Forecast (x) and observed (solid lines) river stages along the Mississippi River at St. Louis, Missouri: (a) 7-day forecasts, (b) 9-day forecasts, and (c) 12-day forecasts.*

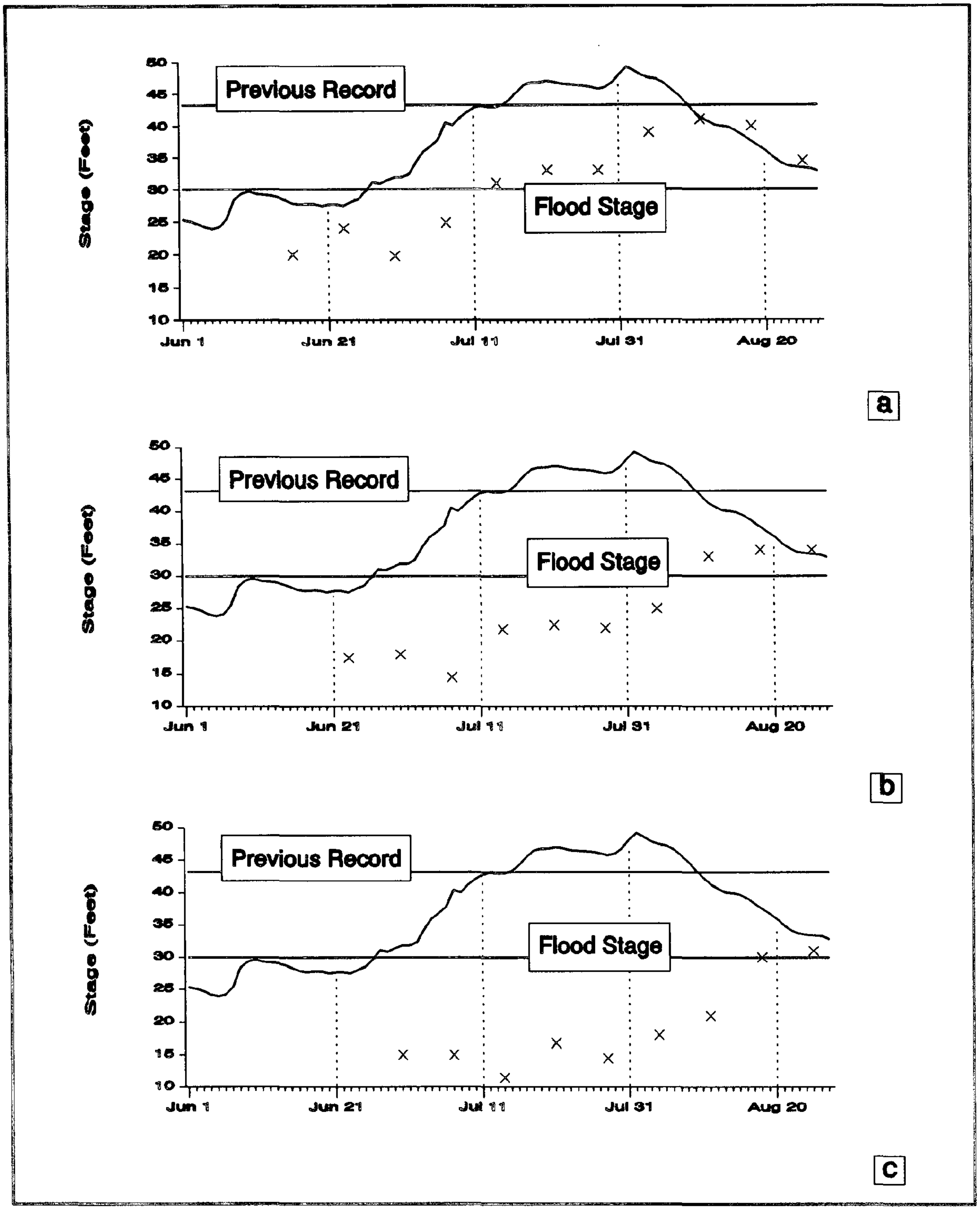


Figure F-3. *Forecast (x) and observed (solid lines) river stages along the Mississippi River at St. Louis, Missouri: (a) 14-day forecasts, (b) 21-day forecasts, and (c) 28-day forecasts.*

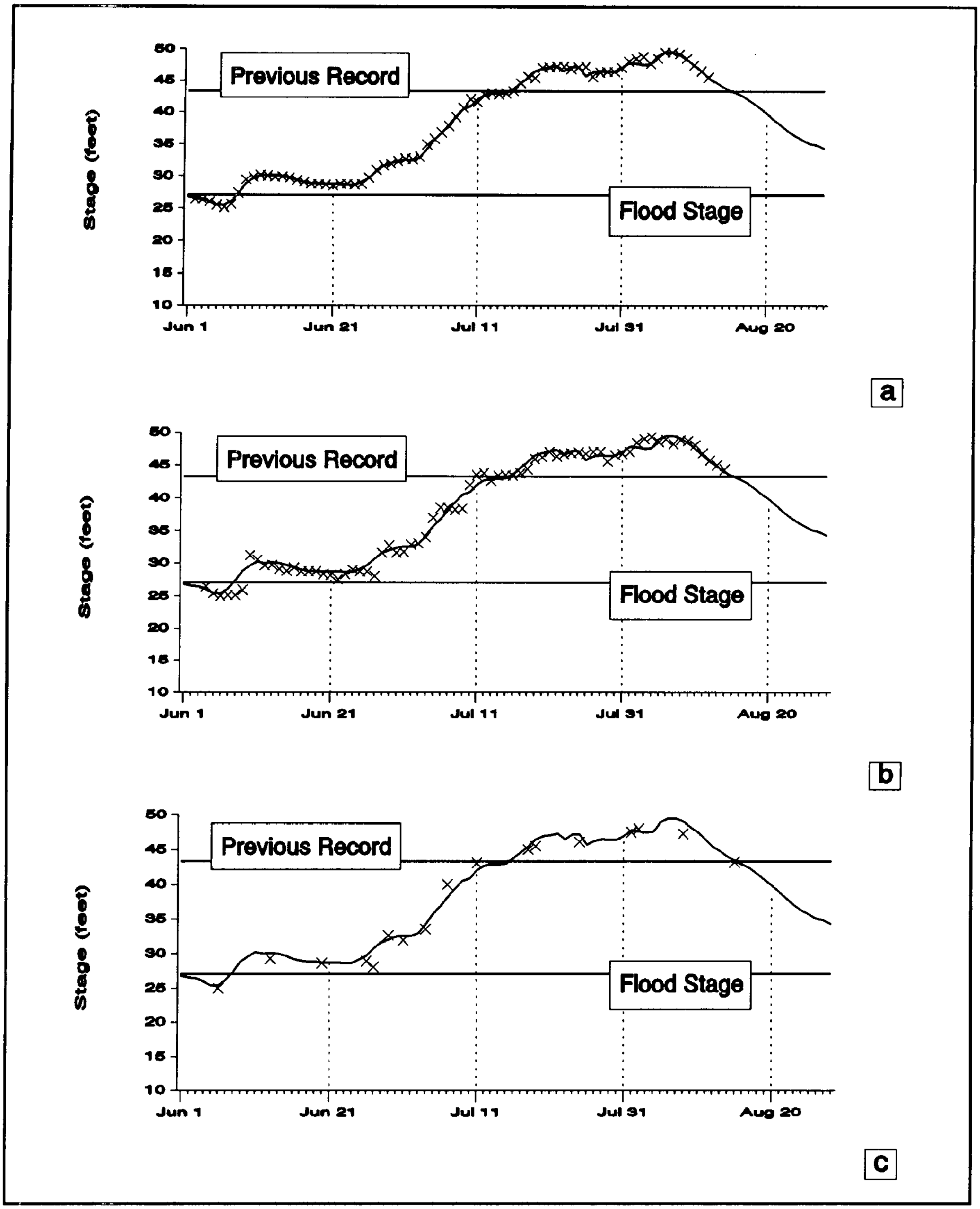


Figure F-4. *Forecast (x) and observed (solid lines) river stages along the Mississippi River at Chester, Illinois: (a) 1-day forecasts, (b) 3-day forecasts, and (c) 5-day forecasts.*

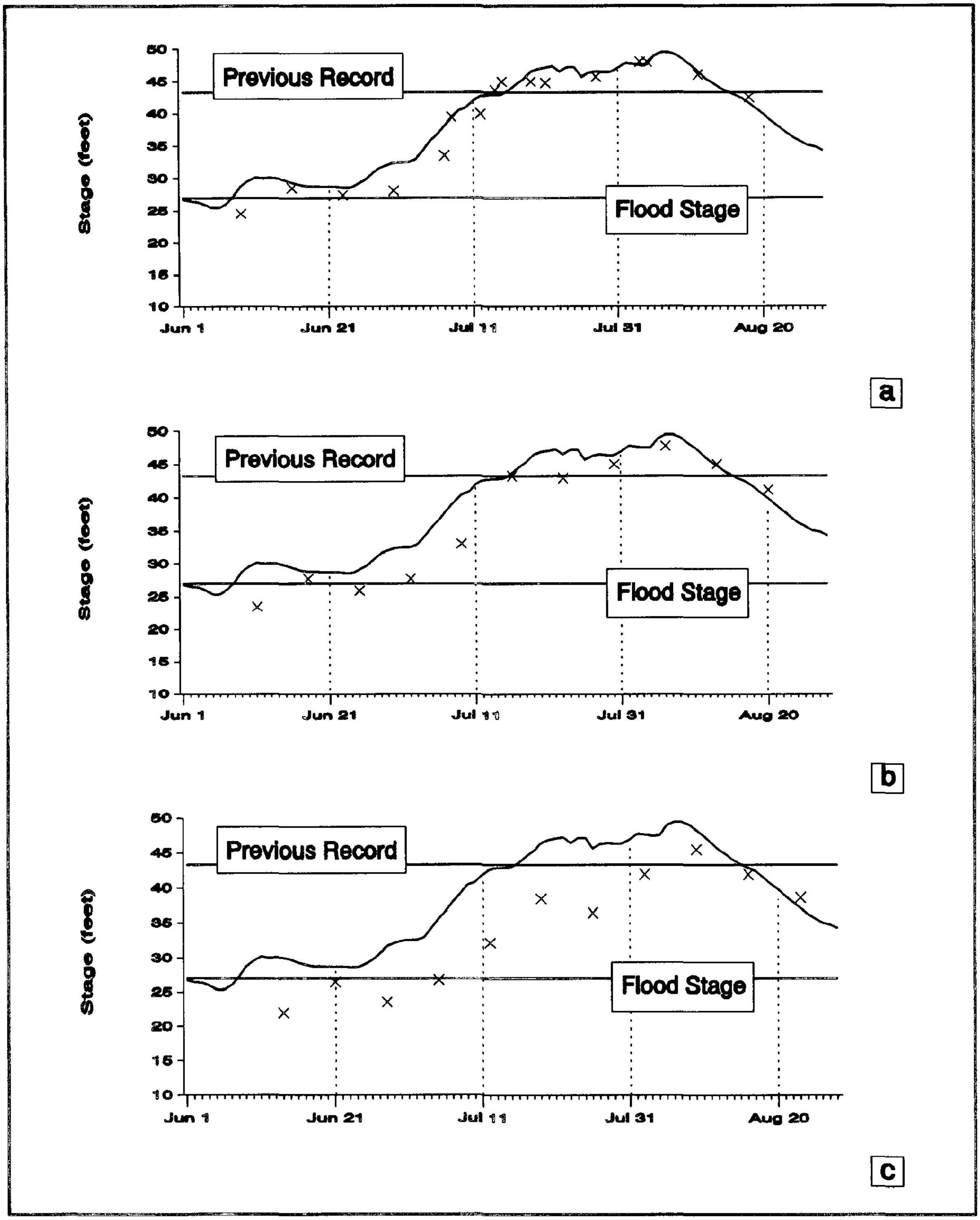


Figure F-5. *Forecast (x) and observed (solid lines) river stages along the Mississippi River at Chester, Illinois: (a) 7-day forecasts, (b) 9-day forecasts, and (c) 12-day forecasts.*

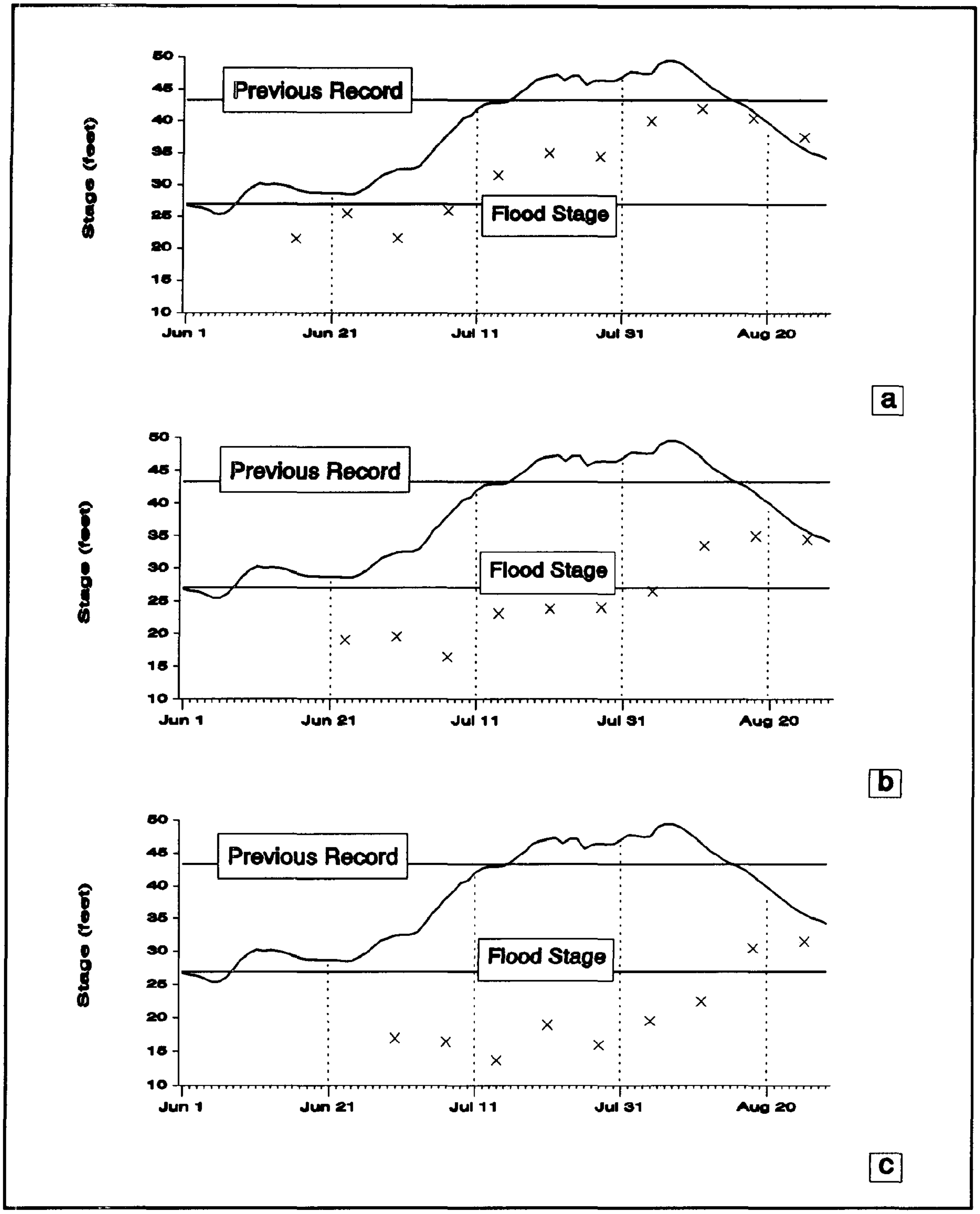


Figure F-6. *Forecast (x) and observed (solid lines) river stages along the Mississippi River at Chester, Illinois: (a) 14-day forecasts, (b) 21-day forecasts, and (c) 28-day forecasts.*

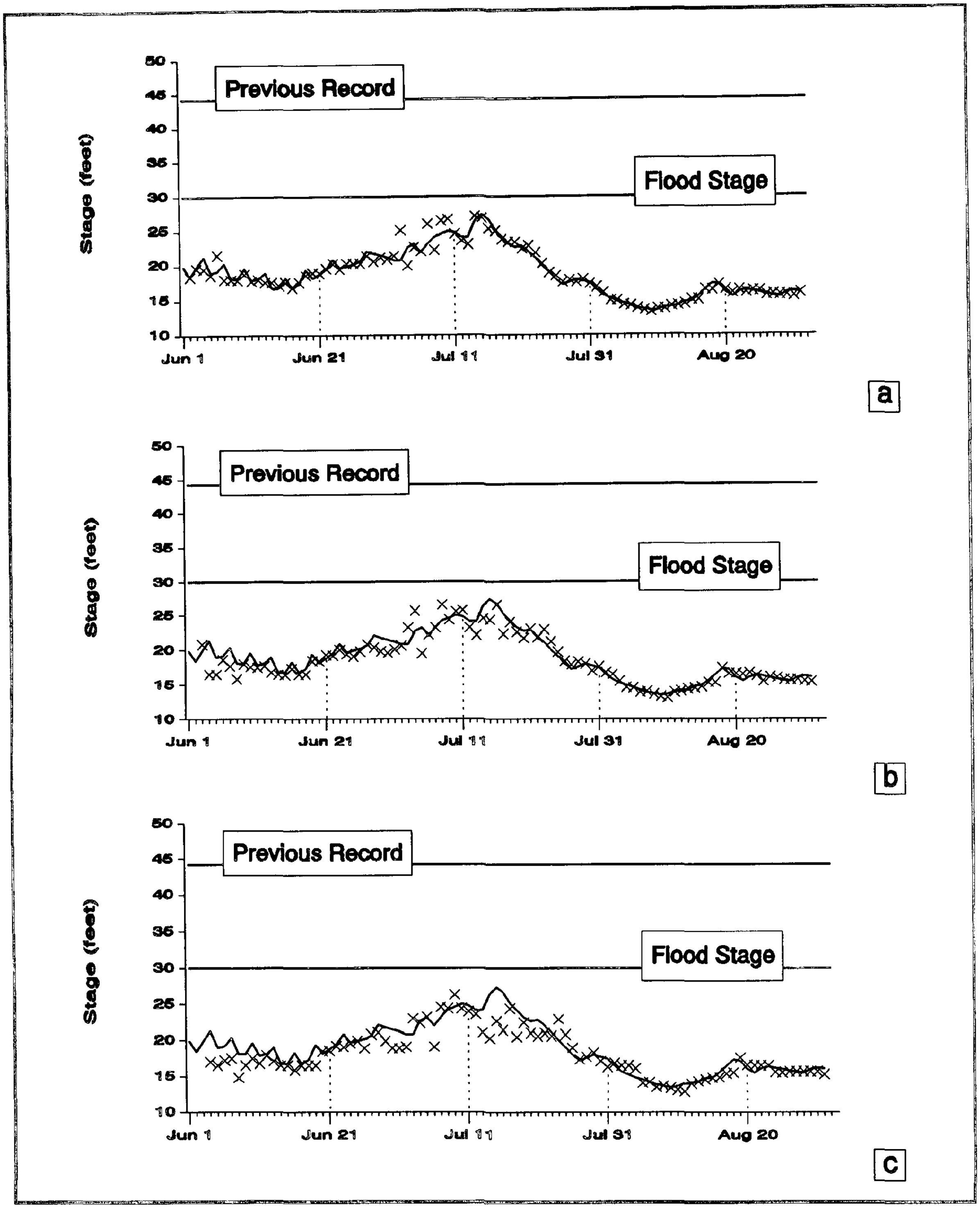


Figure F-7. *Forecast (x) and observed (solid lines) river stages along the Missouri River at Sioux City, Iowa: (a) 1-day forecasts, (b) 2-day forecasts, and (c) 3-day forecasts.*

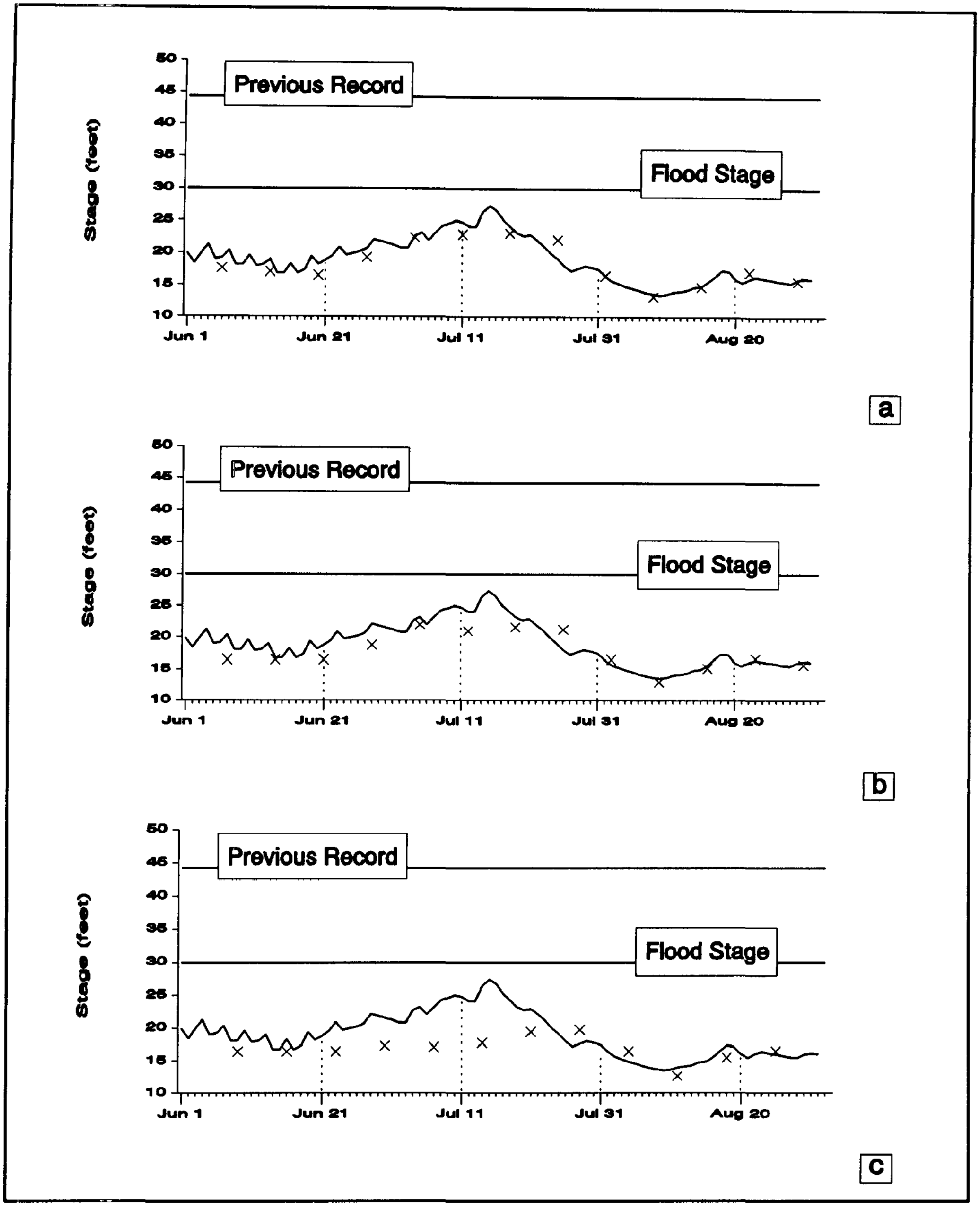


Figure F-8. *Forecast (x) and observed (solid lines) river stages along the Missouri River at Sioux City, Iowa: (a) 4-day forecasts, (b) 5-day forecasts, and (c) 7-day forecasts.*

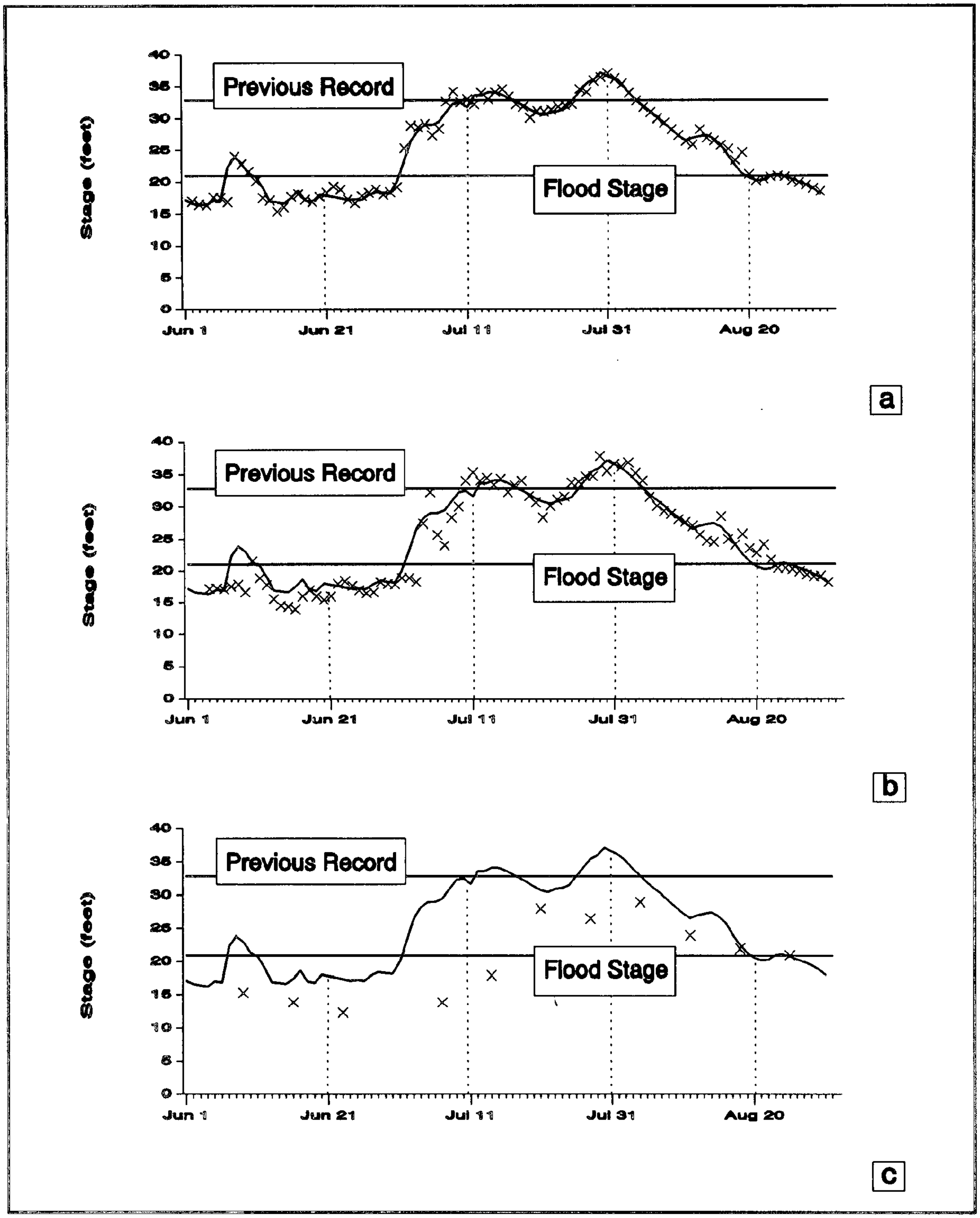


Figure F-9. *Forecast (x) and observed (solid lines) river stages along the Missouri River at Boonville, Missouri: (a) 1-day forecasts, (b) 3-day forecasts, and (c) 7-day forecasts.*

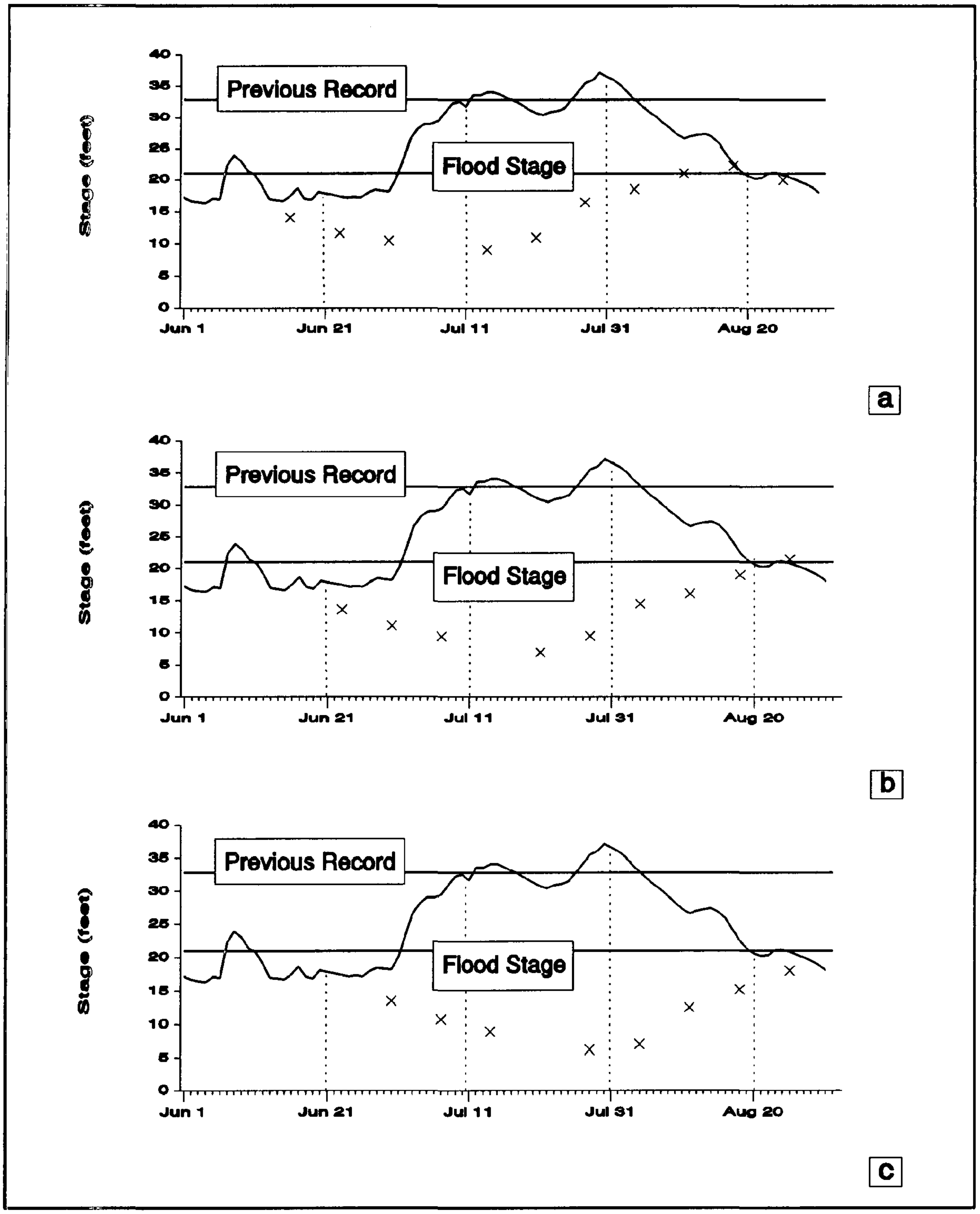


Figure F-10. *Forecast (x) and observed (solid lines) river stages along the Missouri River at Boonville, Missouri: (a) 14-day forecasts, (b) 21-day forecasts, and (c) 28-day forecasts.*

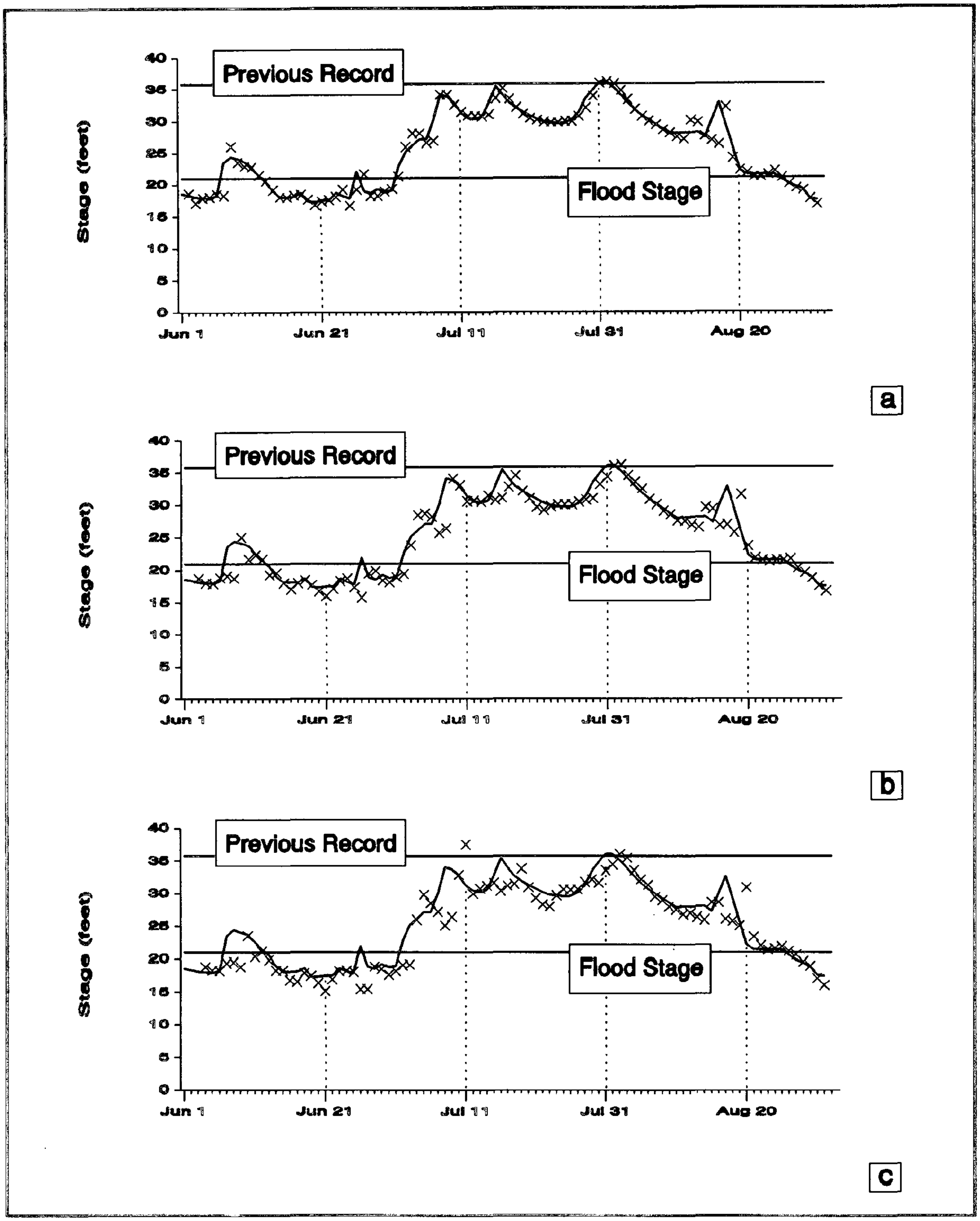


Figure F-11. *Forecast (x) and observed (solid lines) river stages along the Missouri River at Hermann, Missouri: (a) 1-day forecasts, (b) 2-day forecasts, and (c) 3-day forecasts.*

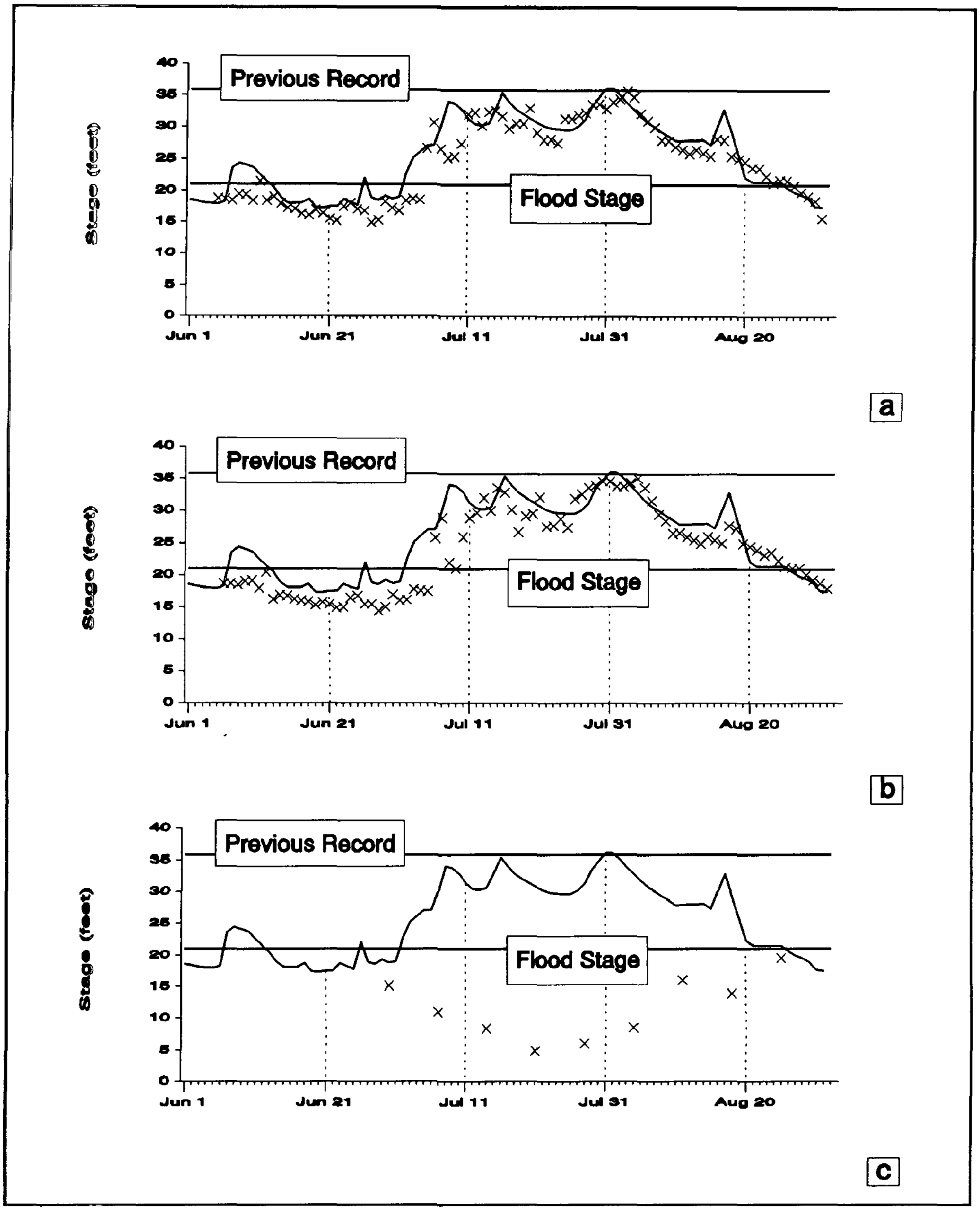


Figure F-12. *Forecast (x) and observed (solid lines) river stages along the Missouri River at Hermann, Missouri: (a) 4-day forecasts, (b) 5-day forecasts, and (c) 7-day forecasts.*

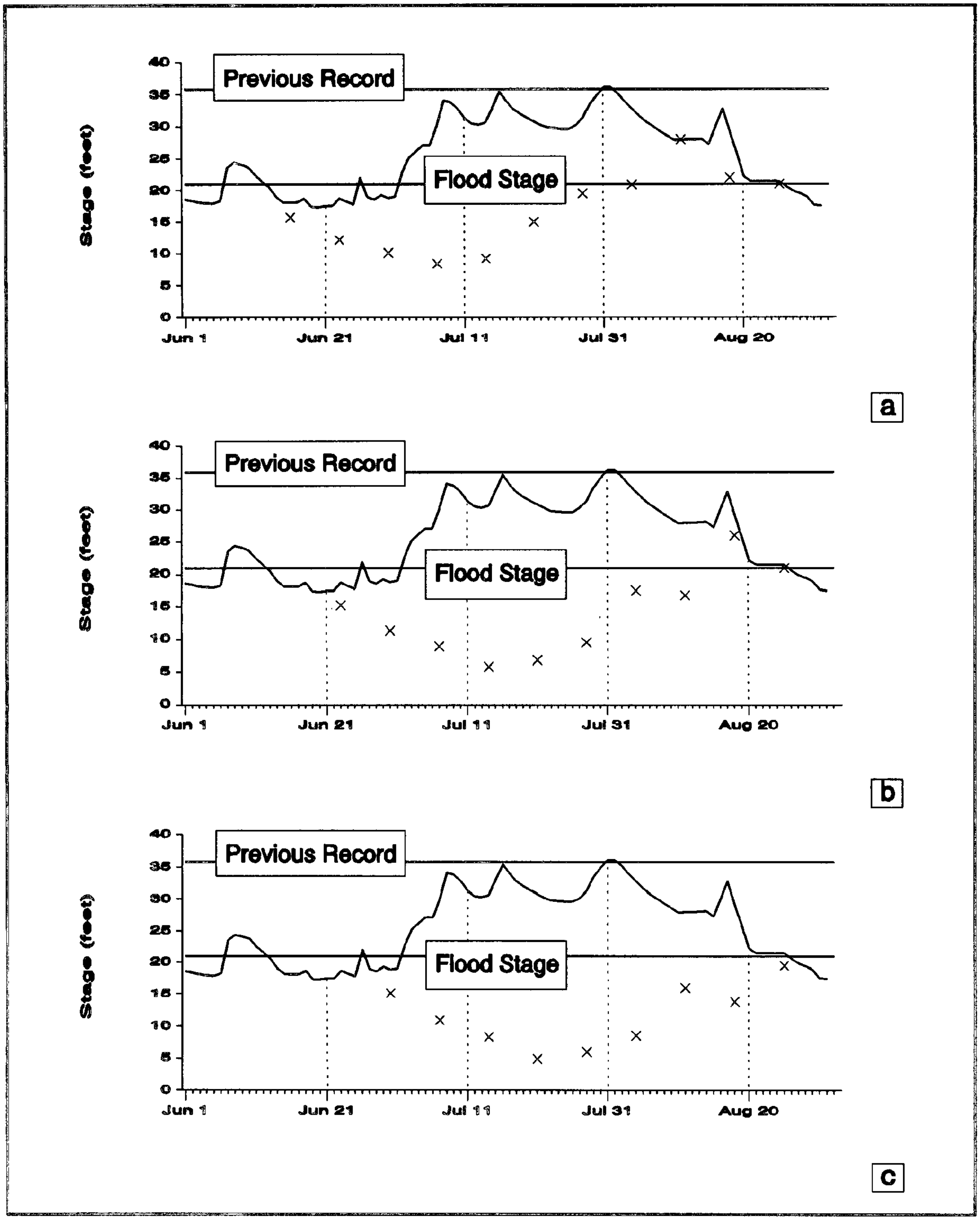
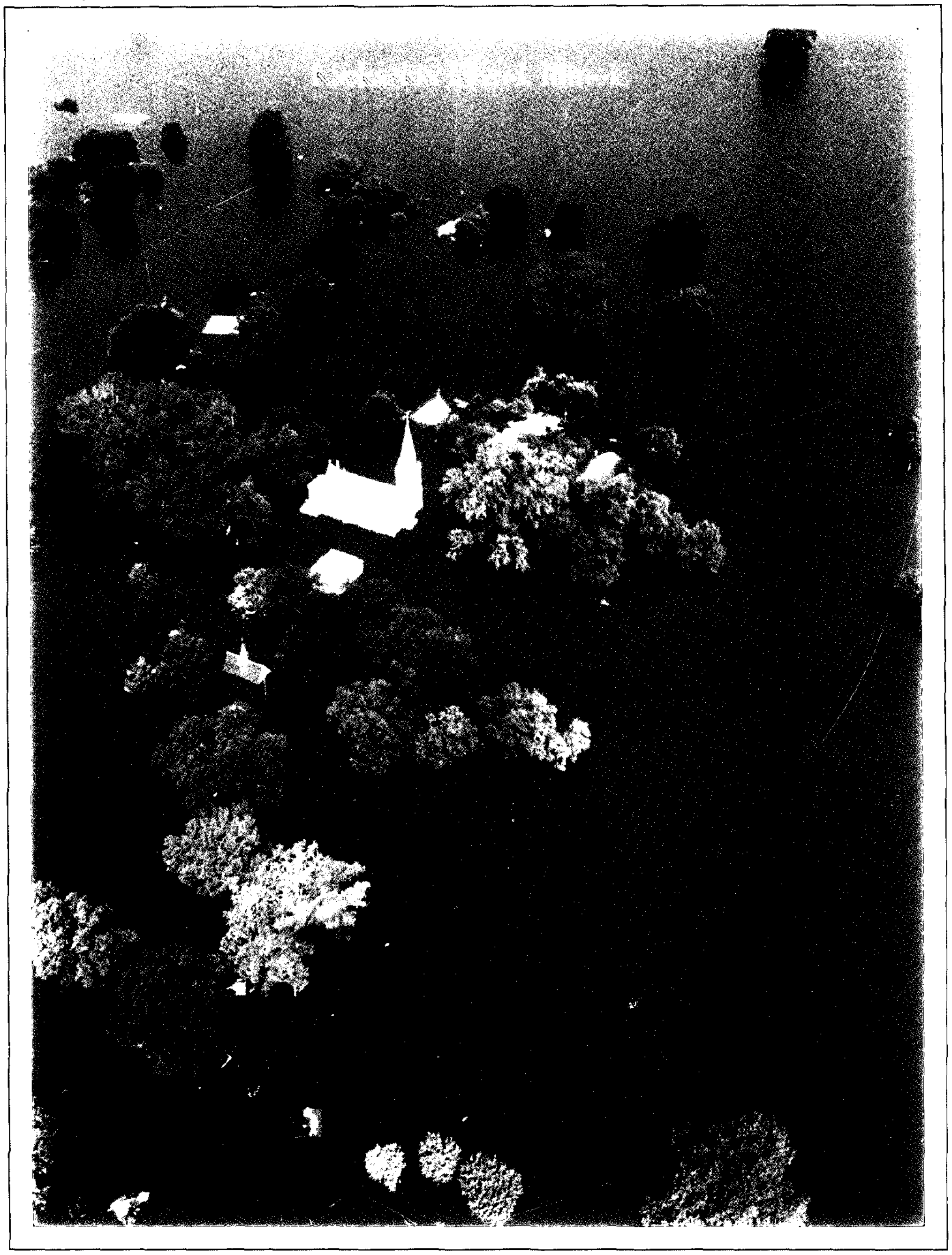


Figure F-13. *Forecast (x) and observed (solid lines) river stages along the Missouri River at Hermann, Missouri: (a) 14-day forecasts, (b) 21-day forecasts, and (c) 28-day forecasts.*



February 1994