98/64

Service Assessment and
Hydraulic Analysis

Red River of the North
1997 Floods

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service
Silver Spring, Maryland

ACTIONS TAKEN FOLLOWING THE RED RIVER OF THE NORTH FLOOD OF 1997

Following the devastating floods of 1997 on the Red River of the North (RRN), the National Weather Service (NWS) has initiated several actions to improve forecast services and take advantage of "lessons learned" from this event to improve NWS river forecast services for the area affected by this flood and for the Nation in general. Some of these actions were taken immediately and have been in place for some time; others are under way as of this writing; still others are in planning phases and depend on budget resources in future years. Some of the actions are highly technical in nature; others involve improvements in coordination mechanisms, policies, procedures, etc. An assessment of NWS services along with a very technical study of the hydraulic characteristics of the 1997 flood in the area of East Grand Forks, Minnesota, and Grand Forks, North Dakota, has now been released in the report, "Red River of the North 1997 Floods Service Assessment and Hydraulic Analysis." This brief document reports the status of the major actions taken since the 1997 floods. Many of the actions were recommended in the preliminary findings of the survey team presented in July of 1997 and are within the final service assessment report.

Before the event was over, NWS had made changes to the rating curve used for the East Grand Forks forecast location, and NWS has continued to update this rating to be consistent with the latest information and analyses provided by the U.S. Geological Survey (which is the agency that collects stream flow information at the site). A widely attended meeting at the NWS North Central River Forecast Center on July 28-30, 1997, provided the forum for a post-flood technical review among Federal agencies (including NWS, USGS, the US Army Corps of Engineers, and the Federal Emergency Management Agency), the Manitoba Water Resource Branch, numerous state officials from North Dakota and Minnesota, and local officials from the Fargo and Grand Forks areas. This technical session addressed numerous coordination and information sharing issues raised by the service assessment. Following this technical meeting, all parties can confirm that they are aware of all of the relevant studies, reports, etc., that may be of value in a future event; and several procedural changes have been adopted in the handoff of information among these organizations (e.g., a revised method to pass forecasts to Canada). Additional planning activities under the aegis of the International Joint Commission (IJC) have continued to involve Canadian and U.S. officials in efforts to improve flood forecast capabilities for the RRN. And a flood planning meeting in Grand Forks on January 21, 1998, brought together local, state and Federal parties with interest in the 1998 snowmelt flood season in the RRN Basin (as well as the Souris basin).

The technical procedures used by the NWS to produce forecasts for the RRN have been looked at in great detail; and several efforts are either under way or planned to improve on these procedures. Those improvements that can be carried out within the existing resource base of the NWS are already under way. These include:

- using the recently completed hydraulic analysis to develop a dynamic routing operation for the East Grand Forks gage site,
- changing the NWS forecast software to provide a more explicit warning when a rating curve extension is in use,
- reviewing the established flood stage for every forecast point on the RRN along with the associated detailed information about flood forecast services and flood impacts,
- recalibrating the RRN Forecasting System using more complete historical data and models that are compatible with the latest NWS forecast methods,
- reviewing some of the unusual flow paths that water took during the RRN floods of 1997 to add an empirical estimate of these overland flows from one stream to another to the NWS modeling procedures where possible,
- developing an enhanced system for analysis and use of snow information, and analyzing the existing flood outlook procedures to determine whether a useful estimate can be provided of the chances that the outlook flood crest will be exceeded.

A few of these technical improvements were available in rudimentary form for the 1998 snowmelt season on the RRN. Presuming that no unexpected difficulties are encountered, all but two will be fully in place for the 1999 RRN snowmelt season — the transition of the RRN Forecast System to recalibrated models throughout will only be partially complete; and the development of an enhanced system for analysis and use of snow information will not be complete.

A far more sophisticated set of model improvements is planned based on the Advanced Hydrologic Prediction System (AHPS). This capability has been prototyped for the Des Moines River in 1997 and is included in the budget submitted for Federal fiscal year (FY) 1999 by the President. Based, in part, on the 1997 floods, the RRN has been identified as the highest priority implementation area for AHPS.

Presuming AHPS budget resources are eventually provided in the FY 1999 appropriation, NWS will:

- proceed to complete an operational forecast procedure for the RRN that includes advanced dynamic routing procedures to account for the complex hydraulics of the entire RRN (not just the East Grand Forks gage),
- develop a method to explicitly account for ponded meltwater in the flat terrain of the RRN,
- look carefully at physically-based methods to model unusual flow pathways at very high flood levels, and, most importantly,
- move the entire forecast system for the RRN into a longer time horizon forecasting methodology that explicitly accounts for forecasting uncertainty and allows for objective risk-based decision making.

As the first area (after the Des Moines prototype) scheduled for full-scale AHPS implementation, the RRN has National implications for the NWS plans for future advanced hydrologic services.

Some of the most important lessons from the RRN floods of 1997 have to do with the way that information is provided to, interpreted by, and used by NWS customers, not just the technical details of how the NWS produces forecasts. Here again, there are actions that have already been taken (e.g., inclusion of discharge forecasts in handoff of data from the NCRFC to Canada, additional explanatory information on outlooks, forecasts, and forecast uncertainty now included in NWS products) for the RRN as well as broader implications for the NWS as a whole. The NWS provided very early information on the risks of severe flooding in the RRN in 1997 and attempted to convey the uncertainty in its forecast products for this event. With the NWS planning changes in its hydrologic forecast products under the AHPS initiative, the lessons learned from the RRN floods of 1997 are of great interest.

The meeting in July of 1997 at NCRFC mentioned above settled many technical matters for the RRN, but the RRN flood event of 1997 also raised coordination issues of National significance: The USGS and the NWS have agreed to review forecast sites for the whole Nation to determine where more complex variable rating models are needed. The NWS will also look into options for enhancing coordination with emergency management officials at state and local levels during similar events, consistent with NWS staff resources.

Finally, the RRN floods of 1997 have led to a review of certain NWS internal procedures:

- The NWS Central Region now has in place methods to order additional telephone services on an emergency basis, with other NWS regions expected to follow.
- An analysis of the feasibility of telephone services to route around a possible major telephone company failure is underway.
- Based on the extraordinary media interest in the RRN flood of 1997, NWS offices immediately affected by that flood have already been trained in ways to be more efficient in supporting the media; extending this training to National coverage is an NWS objective as is developing better and more explicit plans for escalating the NWS response to the media as media interest escalates in any future great flood.

Perhaps it is human nature to focus on the negative aspects of a devastating flood event, but it is well to remember that many of the "lessons learned" during the RRN floods of 1997 are things done well that should be repeated by other NWS offices in future floods — things such as, treating an unusual event in an unusual way by releasing information early and by scheduling early and extra coordination meetings, taking full advantage of the capabilities of the Airborne Gamma Snow Survey Program to quantify the condition of the snow pack, and, overall, coming forward with the extra time and effort to be available to the media and to explain the severity of the threat early and often to local, state, and Federal officials. As a specific example, the NWS Central Region uses the flood preparedness activities led by the Eastern North Dakota office in 1997 as a guide to "best practices" for other offices to follow.

The National Weather Service is committed to providing the best possible forecast services for future floods on the Red River of the North and for the entire Nation within the limits of science, technology, and resources. Actions have been taken already to improve our services to the citizens of the Red River of the North based on the "lessons learned" from the devastating 1997 floods; other actions to improve services are underway or planned that will continue to improve the river forecast information that the NWS provides for the citizens of North Dakota, Minnesota, and the Nation.

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August 1998

U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

National Oceanic and Atmospheric Administration
D. James Baker, Administrator

National Weather Service
John J. Kelly, Jr., Assistant Administrator

PREFACE

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 Nations's economic and environmental well-being.

A survey team was assembled following disastrous flooding on the Red River of the North in April of 1997 which caused $4 billion in economic damages to the affected region in this country and truly devastating damages in the towns of Grand Forks, North Dakota, and East Grand Forks, Minnesota. No deaths were directly attributable to the flood. The survey team consisted of ten members including personnel from the NWS national headquarters and western regions, the U.S. Geological Survey, the U.S. Army Corps of Engineers, and a consultant. The survey team conducted field interviews and data collection from May 27-30, 1997, and provided preliminary results to the media, local officials, and the U.S. Congress in briefings on July 25, 1997.

This report summarizes the findings and recommendations from the survey team's investigations and from a further analysis of the hydraulic conditions in the Grand Forks area. Although the Red River of the North floods of 1997 caused devastating impacts in economic, environmental, and human terms, the lessons learned have already led the NWS to changes that will guide us in providing improved services and benefits to the Nation.

John J. Kelly, Jr.
Assistant Administrator
for Weather Services

FOREWORD

This report of the findings and recommendations of the National Oceanic and Atmospheric Administration (NOAA) survey of the April 1997 floods on the Red River of the North consists of two primary parts: an assessment of the services provided by the National Weather Service in forecasting this devastating event and an analysis of the hydraulics of the flood itself in the vicinities of Grand Forks, North Dakota, and East Grand Forks, Minnesota. The service assessment was completed shortly after the event itself; the results of the service assessment were reported in public meetings and press conferences that were presented on July 25, 1997. There remained one significant set of issues — all related to the reasons that the Red River of the North reached significantly higher stages at East Grand Forks than were expected. The hydraulic analysis in this report is the culmination of a sensitivity analysis designed to clarify the contributions of various factors to this higher-than-expected stage. The National Weather Service (NWS) is committed to providing the best possible flood warnings within the limits of the science, technology, and resources available for the residents of the Red River of the North, in particular, and the Nation in general. The primary impetus of this report is to improve these services. Many of the findings and recommendations of the service assessment portion of this report have already been acted upon and are already part of the NWS flood warning services to the region. The hydraulic analysis, likewise, aids the accuracy of NWS services.

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ACRONYMS AND ABBREVIATIONS

ADD/SUB	NWSRFS modeling operation that adds together the various flows coming into the forecast point (including the local runoff from the UNIT-HG)
AHPS	Advanced Hydrologic Prediction System
BASEFLOW	NWSRFS modeling operation that determines the baseflow contribution to the hydrograph
DAPM	Data Acquisition Program Manager
EAP	Employee Assistance Program
ESP	Ensemble Streamflow Prediction (a feature of NWSRFS used for probabilistic forecasting)
FEMA	Federal Emergency Management Agency
FGF	Call sign for the Eastern North Dakota NWS Office located in Grand Forks, North Dakota, and serving Fargo, Grand Forks, and the entire Red River of the North Basin
HIC	Hydrologist In Charge (of an RFC)
HSA	Hydrologic Service Area
MIC	Meteorologist in Charge (of a WFO)
MKC-API	NWSRFS modeling operation that determines the runoff from the basin (a particular form of Antecedent Precipitation Index model)
NCRFC	North Central River Forecast Center (located in Chanhassen, Minnesota)
NDDEM	North Dakota Department of Emergency Management
NEXRAD	Next Generation Weather Radar (program to deploy NWS doppler weather radars)
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center (collocated with NCRFC)
NWR	NOAA Weather Radio
NWS	National Weather Service
NWSO	NEXRAD Weather Service Office (office designation for NEXRAD-equipped weather office prior to official upgrade to WFO)
NWS FLDWAV	NWS Flood Wave model — a dynamic wave, implicit solution, one-dimensional, hydraulic model
NWSRFS	National Weather Service River Forecast System (a software system used by RFCs for river forecasting)
OFS	Operational Forecast System (a component of NWSRFS)
RFC	River Forecast Center
SEUS-E	Snow Estimation and Updating System - East (a software system that assimilates snow information to update NWSRFS-designed for applications outside the mountainous West)
SAC-SMA	Sacramento Soil Moisture Accounting model (an NWSRFS component)
SNOW-17	NWSRFS modeling operation for snow accumulation and melt

STAGE-Q	NWSRFS modeling operation that converts observed stage values to discharge using the rating curve
TATUM	NWSRFS modeling operation (storage routing procedure) which routes water coming from upstream to the forecast point
UNIT-HG	NWSRFS modeling operation (Unit Hydrograph) that converts runoff from the basin into stream channel discharge at the forecast point
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WCM	Warning Coordination Meteorologist
WFO	Weather Forecast Office

EXECUTIVE SUMMARY

Flooding on the Red River of the North in 1997 established (twentieth century) records at most locations and was particularly devastating in the towns of Grand Forks, North Dakota, and East Grand Forks, Minnesota. With the exception of Grand Forks, which exceeded the previous (1979) record by over 5 feet, observed crests at most other forecast locations on the Red River of the North were about 2 feet above the previous records. Estimated damages for the complete event, including all United States portions of the Red River of the North, totaled about $4 billion, of which $3.6 billion occurred in the immediate vicinity of Grand Forks / East Grand Forks. No deaths directly attributable to the flooding resulted from this event. The National Oceanic and Atmospheric Administration (NOAA) typically conducts a post-event survey for events of this magnitude. The NOAA disaster survey team found instances of innovative and excellent performance and instances where NWS products and services could be improved.

NWS services beginning with early outlooks calling for record flooding and continuing through the flood event itself were generally informative and acceptable at all of the forecast points on the Red River of the North, with the exception of Grand Forks. Forecast errors at Grand Forks were due to the unprecedented complex interaction of hydrologic and hydraulic conditions. This report notes limitations to current flood forecasting techniques and capabilities, identifies areas for improving communications between the NWS and cooperating agencies, and provides recommendations for improving the way the NWS prepares and explains its flood forecasts.

The survey team recommended several steps be taken to improve the hydrologic forecast process through a series of important investments in NWS forecast procedures. The NWS needs to improve the methods used to estimate and convey the uncertain nature of its flood forecasts and outlooks. The most promising methods to address these issues have been prototyped in the Des Moines demonstration of the Advanced Hydrologic Prediction System, which should be extended to National coverage as resources allow.

The survey team found that cooperation among the USGS, the USACE, and the NWS was instrumental to the services the NWS provided. The survey team also supports the interagency technical review hosted by the North Central River Forecast Center (NCRFC) on July 28-30, 1997, in Chanhassen, Minnesota, as an ongoing step in the interagency review of technical methods used to forecast flooding in the Red River of the North.

EVENT OVERVIEW

Floods on the Red River of the North occurred in the context of unusual conditions that led to serious flooding throughout much of the upper Midwest. Beginning in the fall months in 1996, much of the region received substantial precipitation in late October and November. For many areas, this amounted to 4 or more inches above normal. Much of the precipitation occurred as rainfall during October and early November. The soil profile was generally wet to 5 feet even though it was a dry summer; the rains that occurred during November were very efficient in increasing the soil moisture since most, if not all, the rain that fell was absorbed by the soil. Following the wet fall, the north-central U.S. experienced horrific conditions over the winter of 1996-97. Blizzard after blizzard during the second half of November through January built up an enormous snowpack; many areas had more than 100 inches of snowfall. These amounts were as much as 2-3 times the normal annual snowfall. Although February and March were quite dry, frigid conditions throughout much of the winter ensured that as much as 10 inches of snow water equivalent remained on the ground at the start of the spring melt period.

Early March brought below normal temperatures, delaying the onset of snowmelt. By mid-March, the snow line had moved north to the vicinity of the northern Iowa state line. Mid-March saw significant rises and ice jams on the Redwood and Cottonwood Rivers in Minnesota. Additionally, the Blue Earth and Le Seur Rivers began rising, resulting in flood stage being reached on the Minnesota River at Mankato. As this flow from the tributaries of the Minnesota River continued, the Minnesota River rose above flood stage at all gaging locations.

Significant melt of the deep snow cover started with particularly warm conditions at the end of March and into early April. At this time, many rivers in South Dakota, southern Minnesota, and southern North Dakota were rising, in some cases well above flood stage. Conditions changed dramatically over the weekend of April 5-6, with heavy rain in the areas already experiencing melt, followed by more blizzard conditions that brought a foot or more of snow to the northern portions of the Red River of the North Basin in the U.S. This event increased the amount of water destined to flow into rivers by 2-3 inches and all but cut off melt due to temperatures dropping well below freezing; the second week in April saw temperatures that averaged as much as 20 degrees below normal. The cold temperatures effectively halted snowmelt runoff, with shallow and/or slowly moving water freezing rapidly--in some cases, seizing anything that remained, including cars and some livestock. However, the cold did not halt flood flows already moving through rivers in southern Minnesota, eastern South Dakota, and southeastern North Dakota. In addition to the havoc wrought by the snow and cold on transportation and, in some cases, on power distribution, sandbagging became extremely difficult. The reduced runoff and freezing as well as the added snow water equivalent significantly complicated the forecast problem. While temperatures moderated in mid-April, they continued below normal until April 17 when they rose rapidly to above normal with no overnight low temperatures below freezing. Within a week after the early April blizzard, melt resumed, with additional rises on most of the area's rivers and streams. Some of the most serious flooding in the U.S. occurred in the Red

River of the North Basin within North Dakota and Minnesota--the area of coverage of this report. (Serious flooding also occurred in nearby areas of southern Minnesota, particularly on the Minnesota River, on the James River in eastern South Dakota, and on portions of the Mississippi River.)

Flooding on the Red River of the North in 1997 established (twentieth century) records at most locations and was particularly devastating in the towns of Grand Forks, North Dakota, and East Grand Forks, Minnesota. The summary below provides a comparison of differences in the new flood records with previous floods of record (from the twentieth century). With the exception of Grand Forks, which exceeded the previous (1979) record by over 5 feet, observed crests at forecast locations on the Red River of the North were within approximately 2 feet of the previous records. Estimated damages for the complete event, including all United States portions of the Red River of the North, totaled approximately $4 billion, of which $3.6 billion occurred in the immediate vicinity of Grand Forks / East Grand Forks. No deaths directly attributable to the flooding resulted from this event.

Table 1. Red River of the North Flood of 1997 Summary.

Location	Flood Stage	Flood of Record	1997 Crest	Difference of flood of record and 1997 crest
Wahpeton, ND	10	17.95 4/5/89	19.44 4/6/97 & 4/15/97	+1.49
Fargo, ND	17	37.3 4/15/69	39.72 4/18/97	+2.42
Halstad, MN	24	39.0 4/22/79	40.78 4/19/97	+1.78
East Grand Forks, MN	28	48.8 4/26/79	54.35 4/22/97	+5.55
Oslo, MN	28	38.6 4/26/79	38.1 4/23/97	-0.5

Location	Flood Stage	Flood of Record	1997 Crest	Difference of flood of record and 1997 crest
Drayton, ND	32	43.7 4/28/79	45.55 4/24/97	+1.85
Pembina, ND	42	53.8 5/1/79	54.9 4/26/97	+1.1

1. Wahpeton, North Dakota, at the southern end of the Red River of the North established a new record on April 6, then another crest at or above this on April 15; the high water mark from these two crests is 19.44 feet.

FORECASTING METHODOLOGY

Hydrologic Methods for Forecasts

Forecasts for the Red River of the North are produced at the North Central River Forecast Center (NCRFC) using the Operational Forecast System (OFS) of the NWS River Forecast System (NWSRFS). The hydrology of a typical downstream sub-basin in the Red River of the North watershed is modeled with the following NWSRFS operations:

Table 2. Typical Operations in Forecast Model

Operation	Purpose
SNOW-17	Accounts for snow accumulation and melt
MKC-API	Determines the runoff from the basin
UNIT-HG	Converts runoff from the basin into stream channel discharge at the forecast point
BASEFLOW	Determines the baseflow contribution to the hydrograph
ADD/SUB	Adds together the various flows coming into the forecast point (including the local runoff from the UNIT-HG)
TATUM	Storage routing procedure which routes water coming from upstream to the forecast point
ADD/SUB	Adds the baseflow into the routed flow
STAGE-Q	Converts observed stage values to discharge using the rating curve
ADJUST-Q	Updates the simulated discharge values using observed values
STAGE-Q	Converts simulated discharge to simulated stage using the rating curve

Operation	Purpose
PLOT-TUL	Displays selected results of the operations including the outflow hydrograph

A headwater basin would use all of the above operations except the TATUM routing procedure.

Methodology for Long-Range Outlooks

The conceptual methodology for developing numerical spring snowmelt outlooks (peak stage forecasts) in the upper Midwest has remained the same for decades. The process was originally developed and used by the Missouri Basin RFC prior to the creation of the North Central RFC in 1979. The methodology utilizes the same forecasting system (the OFS subsystem of NWSRFS) used to model and develop short-range flood forecast guidance. As such, all watershed components (headwaters and locals) and routing reaches are identical with respect to parameterization, data requirement, physical state, and output.

Spring snowmelt outlooks are based on one scenario of future temperature and two scenarios of future precipitation. The scenario of future temperature reflects a normal spring warm-up that generates a single snowmelt peak during the month of April. The two scenarios of future precipitation are (1) zero future precipitation and (2) climatological normal precipitation.

Procedurally, the outlook simulations are generated by making deterministic "runs" that begin with the current operational model states and extend 60 days into the future. Since the OFS can only support a 30-day forecast run, the process must be run in two steps of 30 days each. While this is awkward, it does not affect the accuracy of the guidance. For simplicity, climatological normal precipitation (scenario #2) through the end of the forecast period is added to the current model-state snowpack at the start of the run. Since these runs are only used to assess the potential spring peak rather than the time-series of spring runoff, this simplification is reasonable. Once the two simulations are made, RFC hydrologists review the model guidance for each forecast point.

1997 Spring Outlooks for the Red River of the North

The 1997 outlooks for the Red River of the North are presented in Figure 1 below; values shown are the second scenario; i.e., they include climatologically normal future precipitation. Note that later outlooks did not change the values from the late February outlooks. The observed crest at all points except East Grand Forks is within 1-2 feet of the outlook and generally 1-2 feet above the previous record stage. At East Grand Forks, the observed crest stage of 54.35 feet is 5.35 feet above the outlook and 5.55 feet above the previous record stage.

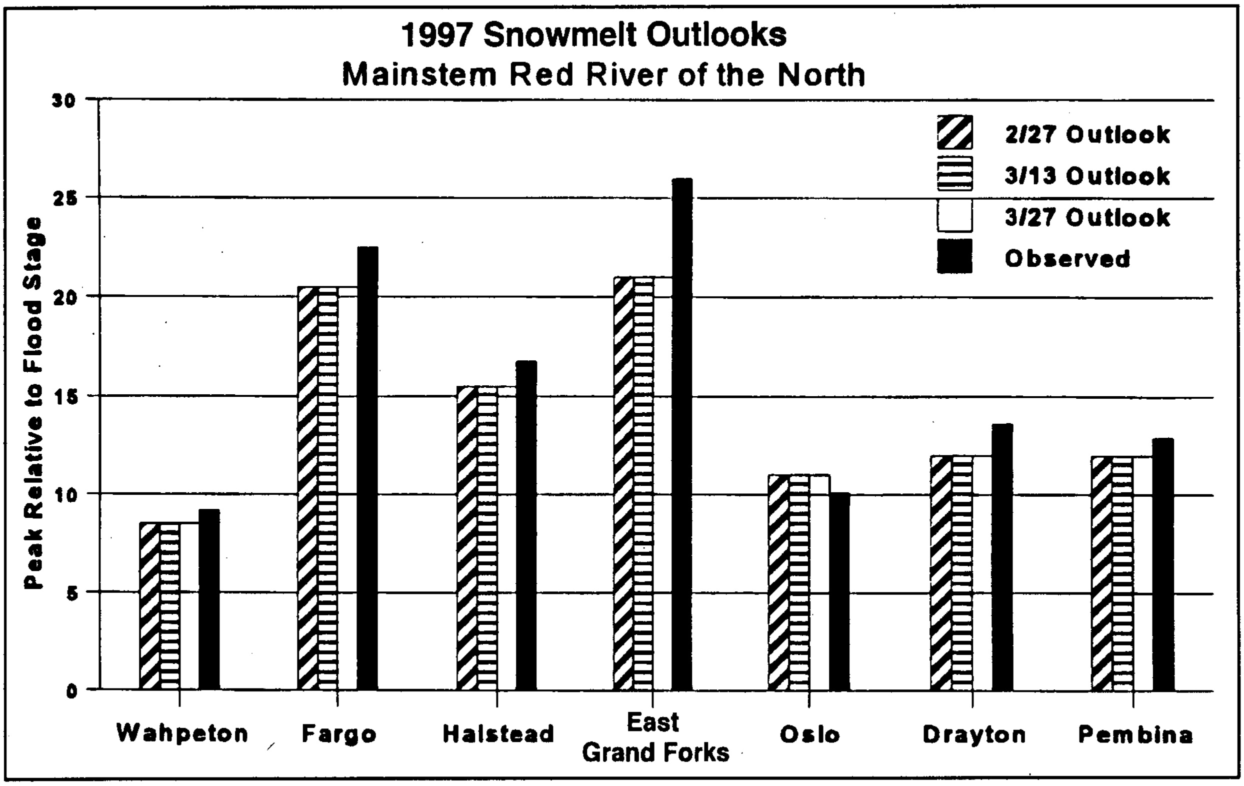

Figure 1. 1997 Snowmelt Outlooks

History of Outlooks for the Red River of the North

Spring Outlook peaks issued for Wahpeton, North Dakota; Fargo, North Dakota; and East Grand Forks, Minnesota, for years 1980 through 1997 are shown below. These are the outlooks issued around March 15 (or earlier) each year. Note that in very low snow years, no outlook value was provided. Columns are (1) forecast snowmelt peak with zero future precipitation , (2) forecast snowmelt peak with climatologically average future precipitation, and (3) observed peak stage.

Table 3. History of Spring Flood Outlooks for the Red River of the North

Year	Location	Outlook Crest No Future Precipitation *(values in feet)*	Outlook Crest Average Future Precipitation *(values in feet)*	Observed Crest Stage *(In feet)*
1980	Wahpeton, ND Fargo, ND EGrand Forks, MN	6.0 15.5 20.0	11.0 21.0 31.0	10.7 20.7 31.0
1982	Wahpeton, ND Fargo, ND EGrand Forks, MN	11.0 22.0 32.0	13.5 30.02 42.0	12.0 25.0 37.1
1984	Wahpeton, ND Fargo, ND EGrand Forks, MN	7.0 17.0 25.0	10.0 22.02 36.0	13.4 28.3 38.2
1985	Wahpeton, ND Fargo, ND EGrand Forks, MN	7.0 17.5 28.0	10.5 22.01 35.0	9.3 17.8 25.8
1986	Wahpeton, ND Fargo, ND EGrand Forks, MN	11.0 22.0 32.0	14.0 28.0 39.0	14.3 27.1 37.9
1987	Wahpeton, ND Fargo, ND EGrand Forks, MN	no outlook no outlook 32.0	 34.0	 33.1
1989	Wahpeton, ND Fargo, ND EGrand Forks, MN	10.0 20.0 31.0	13.0 28.03 40.04	17.8 35.3 44.3

Year	Location	Outlook Crest No Future Precipitation *(values in feet)*	Outlook Crest Average Future Precipitation *(values in feet)*	Observed Crest Stage *(In feet)*
1993	Wahpeton, ND Fargo, ND EGrand Forks, MN	10.0 20.5 27.0	14.0 27.52 37.5	14.3 28.2 35.6
1994	Wahpeton, ND Fargo, ND EGrand Forks, MN	14.0 30.0 39.0	16.0 34.52 42.0	13.3 26.7 33.0
1995	Wahpeton, ND Fargo, ND EGrandForks, MN	11.0 26.0 35.0	13.5 29.02 37.0	14.8 28.4 37.8
1996	Wahpeton, ND Fargo, ND EGrandForks, MN	11.0 24.0 40.0	14.0 28.02 44.54	13.5 28.7 45.8
1997	Wahpeton, ND Fargo, ND EGrandForks, MN	17.0 36.0 47.5	18.5 37.53 49.0	19.2 39.5 54.3

Although the outlooks in Table 3 represent a fairly small sample, a few simple observations are possible: First, the outlooks that assume zero future precipitation have a high likelihood of being exceeded. (As an historical footnote, the "no future precipitation" outlook scenarios were originally developed to aid in evaluation of river transportation issues.) Second, snowmelt outlook peaks that assume normal future precipitation are approximately at the median; i.e., they have approximately a 50 percent chance of being equaled or exceeded. Since the outlook process does not produce an explicit probability of exceedance and the historical sample of outlooks is fairly small, attribution of exceedance probabilities involves a degree of judgement.

Ensemble Streamflow Prediction

The NCRFC has developed the ability to provide probabilistic spring flood outlooks for the Des Moines Basin using the Ensemble Streamflow Prediction (ESP) procedure of NWSRFS. Both traditional (as were done for the Red River of the North) and ESP forecasts for the Des Moines Basin were generated during the Spring of 1997. The ESP procedure was not implemented for the Red River of the North during the 1997 floods.

Rating Curves

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

The USGS is responsible for measuring streamflow throughout the United States. The USGS makes discharge measurements and develops most of the official rating curves used by the NWS. When significant rises occur, the USGS makes additional discharge measurements and routinely provides the information to the NWS, the USACE, and other cooperators. These measurements are used to update rating curves. The rating curves are developed based on actual flow measurements; the USGS does not normally extend them beyond observed flows.

Rating curves are used extensively in the OFS to convert observed stage data into discharge for routing water to downstream points. They are also used to convert discharge at a forecast point into stage values for issuing public forecasts. In some events, the forecast flow or stage is beyond the uppermost value in the rating curve for that location. For those cases, OFS will extend the rating curve by one of three methods: linear extrapolation, logarithmic extrapolation, or hydraulic extension. The method used to extend the curve is defined by the forecaster when setting up the rating curve in OFS. These automatic extensions work well in many situations and are used to provide estimated values until an updated rating curve is available. The extensions may not work well in other situations, especially when significant backwater effects are present. The rating curve in use at the NCRFC for forecasting at the East Grand Forks gage is shown in Figure 2; it includes the portion of the rating curve based on previous (to the flood) observations of the USGS (noted as USGS Rating No. 18), the logarithmic extension within OFS used for forecasting by the NCRFC, and the extension of the rating based on the observations taken during the flood.

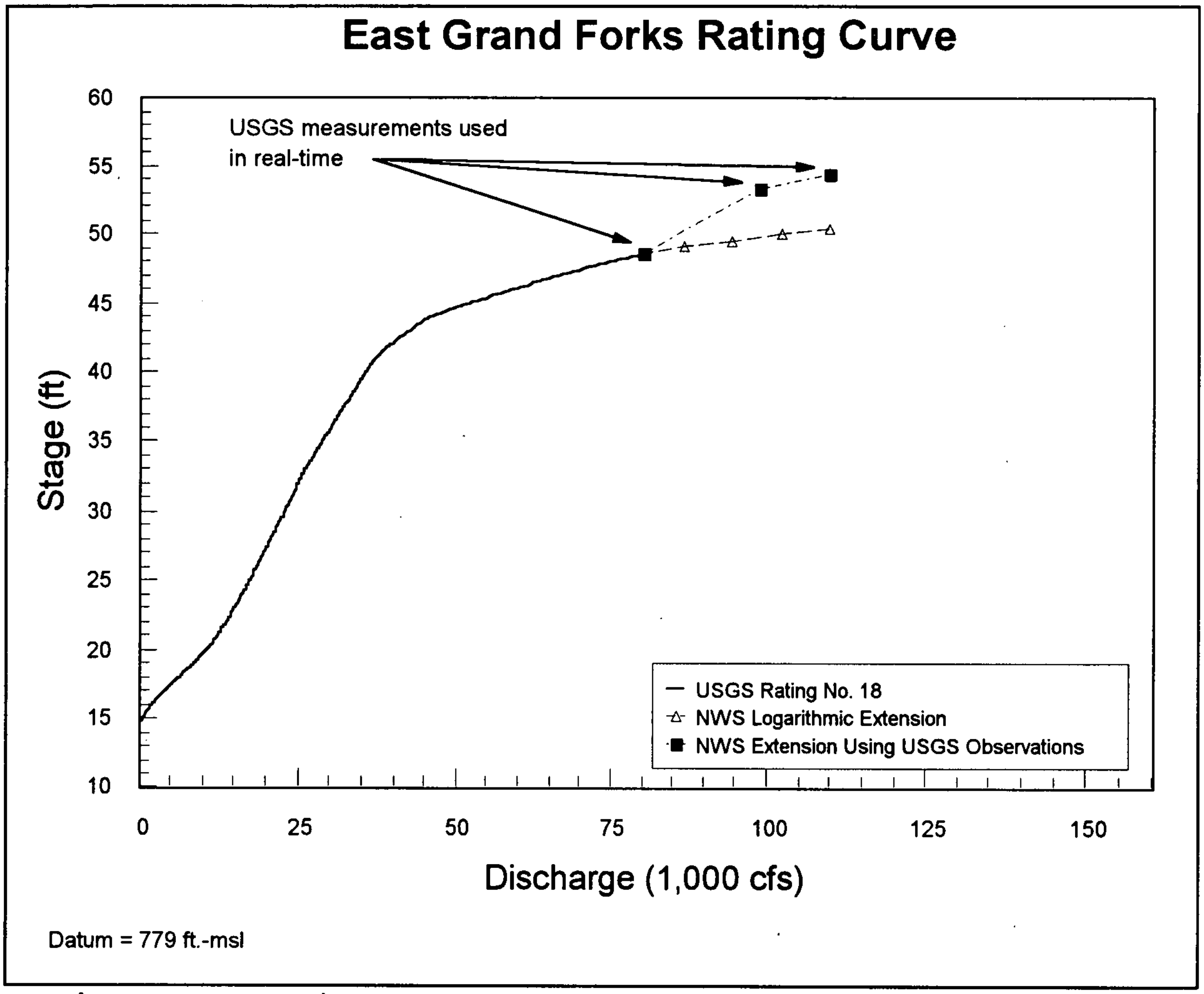

Figure 2 - Rating Curves at East Grand Forks Used by NCRFC.

The hydraulic characteristics of the Red River of the North at Grand Forks and East Grand Forks are very complex. The slope of the river channel upstream and downstream from Grand Forks, inflow from the Red Lake River, and the presence of five bridges connecting Grand Forks and East Grand Forks contribute to a variable relation between river stage and discharge. The official rating curve at a gaged location is a single value function that describes a one-to-one relationship between stage and discharge. Unfortunately, the discharge associated with a given stage may differ depending on whether the river is rising or falling. This effect is particularly dramatic on mildly sloping rivers where significant backwater exists; such as, the Red River of the North. The gradient of the river at flood stage varies from 0.58 foot per mile between Wahpeton and Fargo, to 0.48 foot per mile between Fargo and East Grand Forks, to 0.32 foot per mile between East Grand Forks and Drayton, and to 0.14 foot per mile between Drayton and the International Boundary. The very flat slope downstream from East Grand Forks results in variable backwater conditions depending on ice conditions, debris accumulation, and the volume of runoff flowing into that reach of the river. Under these conditions, small changes in discharge can lead to large differences in stage. This variable stage-discharge relation often appears as a "loop" in the rating curve. The USGS has developed a looped rating curve for East Grand Forks based on the April 1997 flood event, which is shown as Figure 3.

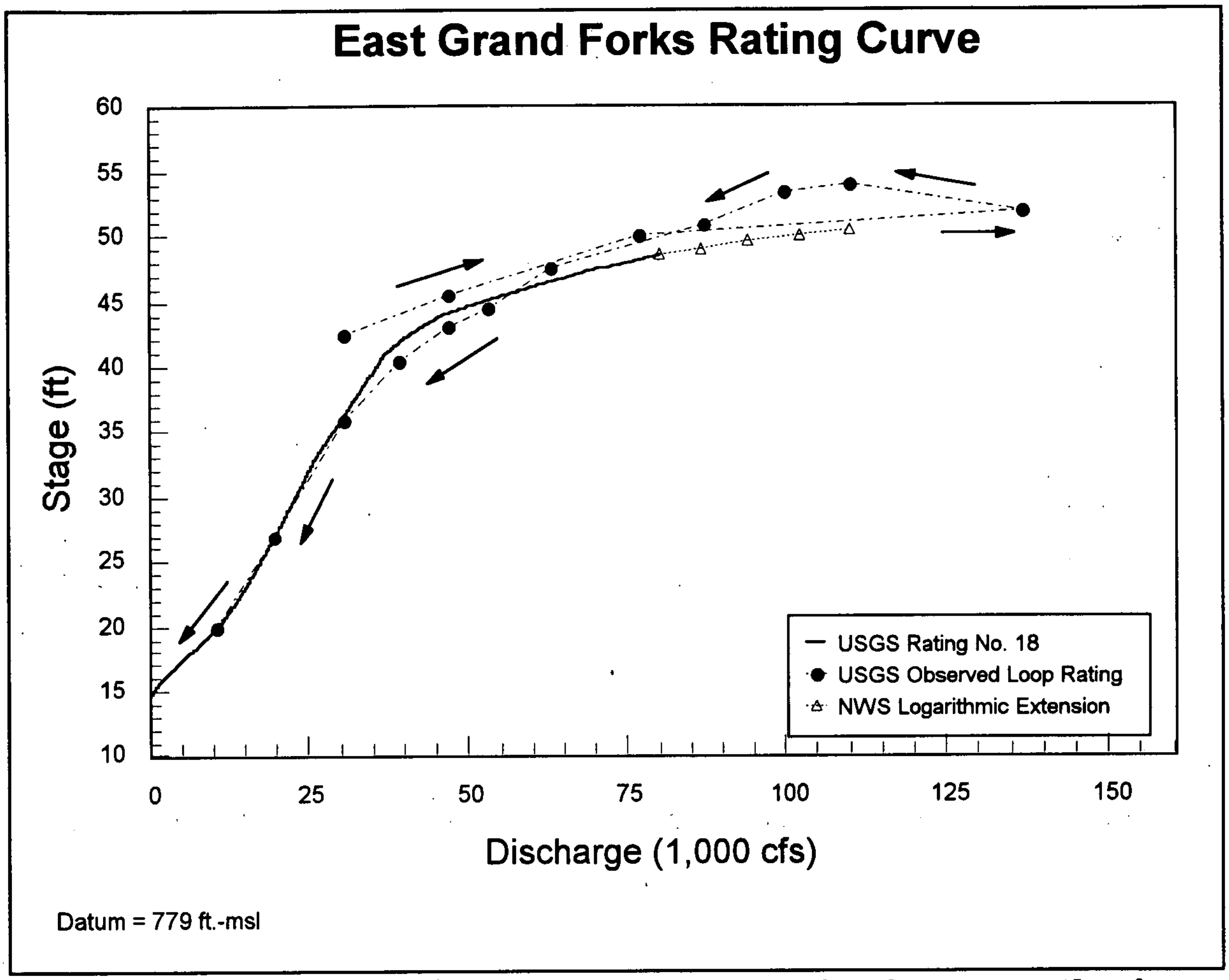

Figure 3 - Loop Rating at East Grand Forks for 1997 Flood.

Finally, it is possible to use hydraulic models in engineering studies to produce a rating curve for hypothetical flood control works or hypothetical flood events. The St. Paul District of the USACE had such a rating curve for East Grand Forks developed as part of a flood control design study for a project which was not built. This rating curve became the subject of some controversy in this event and is included in this report as Figure 4.

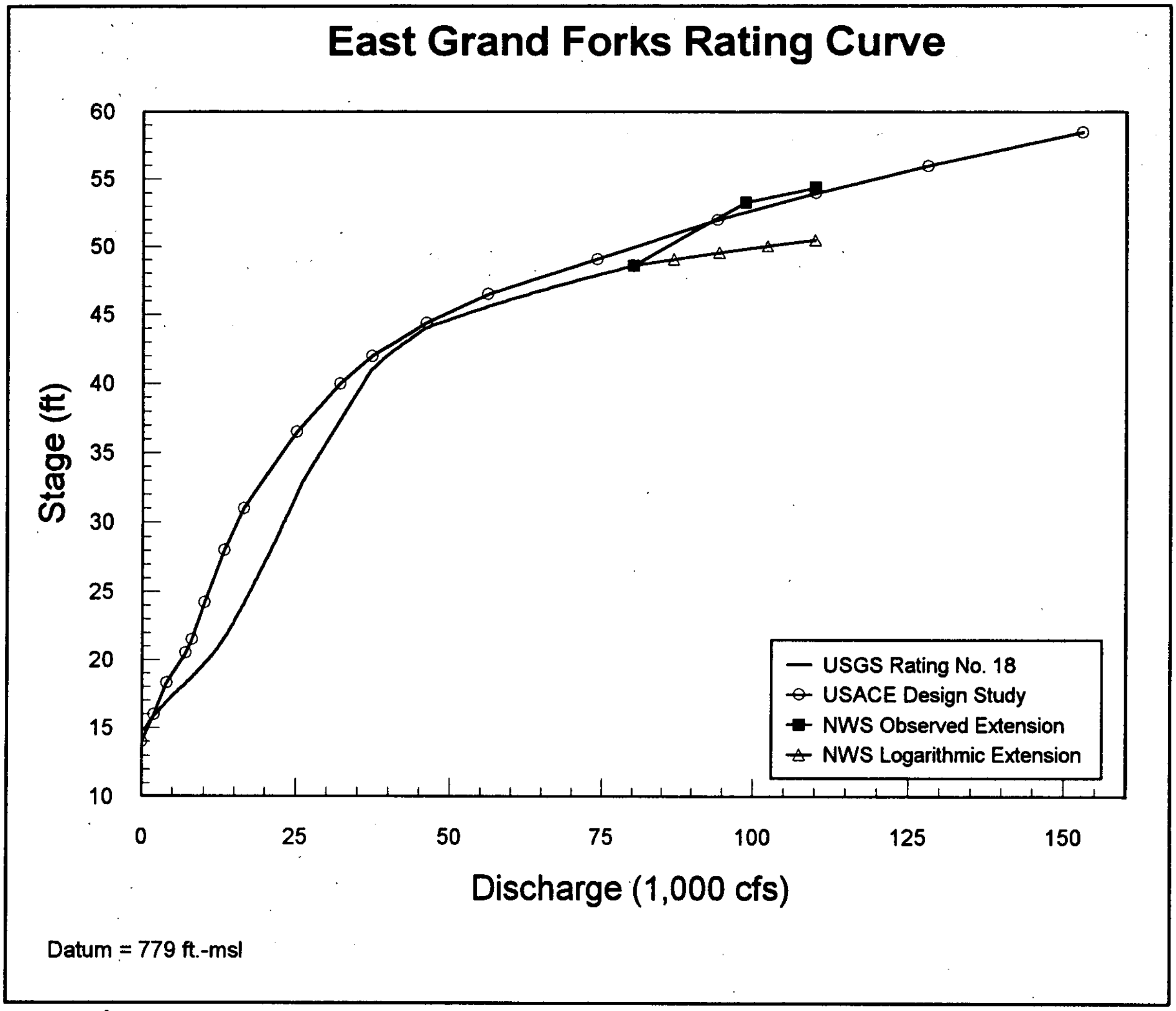

Figure 4. U.S. Army Corps of Engineers Design Study Rating for East Grand Forks, MN

Rating at Grand Forks

The variable stage-discharge relation at East Grand Forks makes it inherently difficult to provide a highly accurate prediction of flood crests (especially for extreme events) there. The discharge measurements made by the USGS during the April 1997 flooding show that the stage varied as much as 6 feet for a discharge of 30,000 cubic feet per second (cfs). Historically, the stage at a discharge of 30,000 cfs has varied between 36 and 40 feet but was affected this year by backwater from downstream ice on the rising limb of the hydrograph to increase the range to 6 feet. Near the peak, the discharge varied from 100,000 to 137,000 cfs while the stage varied between 52 and 54 feet. Measurements made during previous floods show similar variation in the relation between stage and discharge.

The discharge measurements made by the USGS during the April flooding define a loop rating for the East Grand Forks forecast location based on the April 1997 event, but this rating is only representative of conditions during the 1997 flood. The shape and relative position of rating (relation of stage to discharge) varies considerably from year to year depending on ice conditions, debris accumulation, and the volume of runoff flowing into the river at and downstream from Grand Forks. The rating for any individual flood can only be defined precisely with discharge measurements during the flood, which severely restricts the NWS ability to provide an accurate long-range forecast of the flood crest. Using the existing methodology, future flood forecasts should be based on the most recent stage-discharge rating but presented in the context of the range of stages that have been experienced at the predicted peak discharge.

Extensions of the rating curves, based on hydraulic analysis, are routinely done for flood insurance studies by the Federal Emergency Management Agency (FEMA) or during project design by the USACE, city engineers, or other planning agencies. While these engineering analyses may not be directly applicable to a real-time forecast situation, they should be considered on a case-by-case basis to aid NWS forecasters, especially for record and near-record floods. The USACE had such a rating curve for an unbuilt project in Grand Forks. In a post-analysis of the flood forecasting at Grand Forks, the St. Paul District Office of the Corps concluded:

> "The Corps rating curve for Grand Forks was not furnished to the NWS because the curve was a draft working tool used in our ongoing feasibility study for the Grand Forks flood control project to determine top-of-levee elevations. It was not intended to be used as a predictive tool in forecasting flood stages during an emergency. ... The Corps had no reason to believe that their rating curve was more accurate than the official extended rating curve used by the NWS, until after measured flows at Grand Forks exceeded the 1979 flow of 82,000 cfs, (stage 48.8 feet), which occurred early on the morning of 17 April. ... The cities of Grand Forks and East Grand Forks were given the maximum possible time known by either Federal agency to raise their levees, which was on 16 April."

An interagency review by the NWS, USGS, and USACE to examine the extension of the existing rating curves at all forecast points in the Red River Basin could provide an efficient mechanism to improve forecast methods. Since most rating curves provided by the USGS are based on historical records, an effort should be made to review all critical rating curves and any additional information to see if a rating curve can be extended based on information in flood insurance studies, USACE project studies, etc. This review should also confirm that the RFC has current copies of all relevant engineering studies, etc., for the basins in their forecast area.

Although a single-valued rating curve cannot define conditions completely, existing single-valued rating curves for all points along the Red River of the North should certainly be updated with new ones developed from the 1997 data. This should be accomplished through the usual process of updates by the USGS based on the 1997 data.

To achieve maximum accuracy in stage forecasts at East Grand Forks, a considerably more complex hydraulic routing model than the one available during the 1997 flood would be needed. The implementation of such a model needs to establish the performance of the new routing for a variety of historical floods, including the 1997 flood, and the sensitivity of the routing model to real-time observations to account for ice effects and other year-to-year variations. Since it will be used in real-time forecasting, stability of the solution procedures under a wide range of flows must be assured as well.

An hydraulic analysis (see Appendix B) has been performed to understand the hydraulic characteristics that led to the difference between the NWS forecast stage at East Grand Forks based on the NWS simulated hydrograph using the initial extended rating curve used by the NWS and the actual stage at East Grand Forks. The analysis concludes that this difference (which totals ~3.8 feet) is due to the following factors: the effects of the very mild channel slope which produced an unsteady loop rating effect (2.0 feet), the effects of the bridges (0.8 foot), the fact that the NWS simulated discharge hydrograph did not capture the peak discharge which occurred early in the event (well before the peak stage) (0.4 foot), effects from the overtopping of the levees in the Grand Forks area (negligible), and unexplained effects (0.6 foot). A detailed discussion of these effects is contained in Appendix B.

Finding 1: The complex hydraulic characteristics of the Red River of the North at Grand Forks and East Grand Forks were difficult to model with the NWS forecast methods in place during the April 1997 flood. This was the primary reason for the forecast error at that location.

Recommendation 1A: The NCRFC should immediately include new rating curves in the NCRFC modeling system as soon as the USGS updates all single-valued rating curves for the Red River of the North to reflect data from the 1997 flood.

Recommendation 1B: The NCRFC should conduct an interagency review of all available data that might be applicable to the hydraulics of the Red River of the North.

Recommendation 1C: The NCRFC should review the hydraulic study of this report for its applicability to the existing forecast procedures at East Grand Forks and use it as the basis to develop a more sophisticated model for the rating at East Grand Forks.

Recommendation 1D: The NCRFC should develop a plan for implementation of dynamic routing procedures for real-time forecasting for the entire Red River of the North.

The rating curve extensions performed automatically within OFS are required to complete the forecast model execution but may lead to inaccurate stage forecasts. For example, on April 14, NCRFC forecast a peak discharge of 110,000 cfs at East Grand Forks. Because this was above the top of the USGS rating curve available at that time, the OFS used the log-log extrapolation technique (as selected by NCRFC) to translate that discharge to stage. Manual adjustments to the rating curve in East Grand Forks were made by RFC forecasters later during the flood event (see Figure 2). The Tulsa-Plot of the API Model used by the NCRFC to display forecast conditions on the Red River of the North during the 1997 flood does provide a visual cue that the rating has been extended but not an explicit warning message.

Finding 2: The rating curve extensions performed automatically within OFS are required to complete the forecast model execution but may lead to inaccurate stage forecasts.

Recommendation 2: The OFS should provide a clear warning when a forecast goes beyond the top of a rating curve so the forecaster is aware of it and can determine whether the extension is appropriate.

The variable stage-discharge relation for the Red River of the North at East Grand Forks is not unique. Such variable relations can occur on any river with very flat slopes or reaches of rivers affected by inflows from major tributaries or tides. Acting together, the NWS and USGS have the ability to conduct a joint review of all NWS forecast locations to determine which ones could be affected significantly by variable stage-discharge relations in future flood forecasts and whether the use of a looped rating numerical model is warranted on the basis of improved forecast accuracy.

Finding 3: The potential for impacts of variable stage-discharge relationships on NWS river forecast accuracy is not unique to Grand Forks.

Recommendation 3: The NWS and the USGS should add a parameter to their joint review of the relationship between NWS forecast locations and USGS stream gage sites to identify those sites where development of a looped rating is warranted for use in flood forecast operations.

Spring Flood Outlook Methods

While the two scenarios of snowmelt peaks have been provided for many years, they lack information that allows NWS users to better assess a reasonable level of risk. Further, the user is provided with scenarios of zero and normal future precipitation; but a scenario that reflects above average future precipitation is not provided.

NWSRFS supports the ability to develop probabilistic long-range forecasts through the Ensemble Streamflow Prediction (ESP) process. ESP provides a frequency distribution of future outcomes (e.g., peak streamflows) that can be sampled at any desired level of exceedance and associated risk . The streamflow simulation model currently deployed in the Red River of the North (Kansas City API) cannot provide an objective estimate of forecast uncertainty and is not compatible with ESP.

Although it will require a multi-year effort and significant resources, the best method to improve the Spring Outlook process is to make a series of significant investments in NWS forecast procedures. These all point toward implementing ESP to produce the spring snowmelt outlooks at several levels of exceedance probability. This would allow NWS customers to have an objective basis to assess a reasonable level of risk and better understand the uncertainty associated with the guidance values. Implementation of ESP will require the calibration of a continuous streamflow simulation model; such as, the Sacramento Soil Moisture Accounting (SMA) model. The NCRFC should develop a phased plan for recalibration of the Red River of the North using a model that is compatible with ESP. Consideration of river ice effects on stage will also have to be considered within an ESP implementation used for Spring Outlooks.

Implementation of the Advanced Hydrologic Prediction System (AHPS) (demonstrated in 1997 in the Des Moines River Basin) which includes ESP and probabilistic flood inundation mapping would provide additional information to users as to where flooding might occur in cities along the Red River of the North.

Finding 4: The streamflow simulation model currently deployed in the Red River of the North (Kansas City API) is not compatible with ESP.

Recommendation 4: The NCRFC should develop and execute a phased plan for recalibration of the Red River of the North using a model that is compatible with ESP.

Ponded Surface Water Not Modeled

It was observed that much of the meltwater remained ponded on fields due to the very flat terrain and snow and ice that initially blocked culverts until these temporary obstructions melted.

NWSRFS does not contain a hydrologic operation that will model the temporary storage of meltwater that accumulates before conveyances open and allow movement to the stream channel. This inadequacy was circumvented subjectively by manually reducing the melt rate prior to runoff and then enhancing the melt rate once runoff began.

Finding 5: NWSRFS does not contain a hydrologic operation that will model the temporary storage of meltwater that accumulates before conveyances open and allow movement to the stream channel.

Recommendation 5: The Office of Hydrology should develop a method to model the temporary storage of meltwater and add it to NWSRFS.

River Forecast Site Information (E-19) Needs Review

The NWS Form E-19 conveys site-specific information regarding river forecast locations to forecasters who have often never seen the site for which they are forecasting. Accurate and complete information in the E-19s is critical to the forecast process at RFCs and WFOs. The E-19 information for the Red River of the North forecast points could be improved and expanded to include additional information to aid forecasting (which is a common issue for the entire NWS hydrologic services program). E-19s focus on the history of floods and their impacts and on information about measurements at the site. E-19s usually do not include detailed information on local structures and topography that might affect floods at levels above the historical floods; e.g., at the time of the flood, the E-19 for East Grand Forks, Minnesota, did not include a description of the five bridges that cross the Red River of the North within the city. (The only reference to a bridge was that the railroad bridge becomes inoperative at 50 feet.) The established flood stage of 28 feet at East Grand Forks is well below the level that causes damage in Grand Forks itself, due to the levee protection that is in place, although at the 28-foot level certain actions are needed in the city infrastructure and minor flooding may begin upstream.

The Eastern North Dakota office in Grand Forks should review and update the existing E-19s for the Red River Basin, including the defined flood stages. These should include updated impacts and photographs of the surrounding area. The plans for future use of the E-19 information in digital form to control product formatting provides added impetus to these updates.

Finding 6: The E-19 information for the Red River of the North forecast points could be improved and expanded.

Recommendation 6: The Eastern North Dakota office in Grand Forks should review and update the existing E-19s for the Red River Basin, including the defined flood stages.

Forecasts Did Not Include Discharge

The NCRFC provided stage but not discharge values in its forecast products. In conferences with the USACE and others, both stage and discharge values were discussed by NCRFC staff (at least at some points). Including discharge in selected forecast products would provide additional information to sophisticated users (emergency managers, city engineers, USACE, etc.) to independently evaluate the assumed stage-discharge relationship.

Finding 7: The NCRFC provided stage but not discharge values in its forecast products.

Recommendation 7A: NCRFC should include both stage and discharge in information exchanged with water managers.

Recommendation 7B: All NWS RFCs should include both stage and discharge in information exchanged with water managers.

Transbasin Flows Not Modeled

At record flood levels, water may flow in areas where it has never been observed to flow before, including overland flows of water across low points between two streams. Transbasin flows were reported by observers in numerous locations during the 1997 Red River of the North flood event. This information was useful qualitatively, but the condition made forecasting more difficult. At a few locations where transbasin flows are fairly common, the current forecast system has empirical procedures that estimate these flows, but the current forecasting system cannot estimate these flows at locations where they rarely (in some cases never before 1997) occur, and there was no quantitative estimate of the amount of transbasin flow that could have been used to make adjustments in the current forecast system. Even if a dynamic wave model were installed for the Red River of the North, it would require significant additional effort to model transbasin flows with geographic information system methods applied to high-resolution topographic information (which is not currently available) to extend the model to include definition of topographic features that allow transbasin flows to occur.

Finding 8: The current forecasting system for the Red River of the North cannot simulate transbasin flows that occurred at the very high flood levels in the 1997 flood.

Recommendation 8A: NCRFC cannot realistically add physically-based transbasin flow simulation to its current forecast procedures and should, therefore, continue to rely on empirical / subjective estimates of the effects of transbasin flows for the near term.

Recommendation 8B: The feasibility of adding physically-based transbasin flow procedures to a future advanced hydraulic model should be included in the plan for dynamic routing recommended above. (See recommendation 1D.)

Snow Surveys and April Blizzard Effects

The National Operational Hydrologic Remote Sensing Center (NOHRSC) conducts airborne snow surveys which provide critical information for forecasting in the upper Midwest. In 1997, NOHRSC conducted seven airborne surveys over the Red River of the North Basin (see timeline in Appendix A). This unusually large number of surveys was the result of the exceptional snow conditions in the area. Two of these surveys are of special note: The first survey, conducted on February 6-9, 1997, provided much of the justification for the earliest outlook that characterized the potential for spring flooding as "severe."

The blizzard that struck the Red River of the North Basin in early April dramatically altered the hydrologic situation. Data collection and communications were seriously hampered, and full assessment of the storm's impact on the hydrology was not possible for nearly a week after the storm ended. Generally, crest outlook values would not have been exceeded if this blizzard had not occurred. Responding to a request by the NCRFC, the National Operational Hydrologic Remote Sensing Center (NOHRSC) of the NWS Office of Hydrology terminated an airborne snow survey in progress elsewhere and collected snow water data for the Red River of the North on April 9-12. The basin estimates provided to the NCRFC on April 13 provided critical information. This was especially true since much of precipitation data required by the model to simulate snow cover was unavailable as a result of communication failures caused by the severe blizzard conditions.

Finding 9: The airborne snow survey program provides unique information that is critical to accurate snowmelt outlooks and flood forecasts in the Red River of the North. The program was able to respond quickly to a critical, special request to collect snow water observations.

Recommendation 9: The NWS should continue to set aside funds to support routine and special airborne snow surveys for the Red River of the North Basin.

Snow Updating Methods

Current spatial snow water estimation procedures do not make full and optimal use of all available information. Further, the spatial estimates for basins are provided to the model as "perfect" data without regard to the potential for introduced bias or variance. The NOHRSC is developing a Snow Estimation and Updating System for the Eastern U.S. that will allow integration of the ground-based, airborne, radar, and satellite snow data to derive snow water equivalent estimates and optimally update the snow model.

Finding 10: Current methods used by NCRFC to integrate snow observations into forecast models could be improved.

Recommendation 10: The NCRFC and the NOHRSC should develop an implementation plan for the SEUS-E procedure for the Red River of the North.

SERVICE DELIVERY

Flood Preparedness Coordination Effective

The NCRFC and NWSO FGF recognized the potential for dangerous floods in the Red River of the North in 1997 well in advance and made a concerted effort to advise the public of the impending hazard. The NCRFC treated the flood as a non-typical event by issuing early narrative and numerical outlooks. Coordination was vigorously pursued by NWSO FGF and the NCRFC with local agencies throughout the Red River of the North Basin, and meetings were better attended than usual. For example, a meeting on February 27, 1997, was an added "pre-flood" coordination meeting with about 50 participants set up by the Service Hydrologist (SH) at NWSO FGF. An early numerical outlook issued by the NWS on February 28, 1997, was used as justification by USACE to obtain $8 million in early flood-fighting monies. Early use of news conferences by the Eastern North Dakota Forecast Office in Grand Forks to highlight flood outlooks raised public and intergovernmental attention to the likelihood of Red River of the North flooding. In a National press conference on March 18, the Director of the NWS was quoted as predicting record-breaking floods on the Red River of the North in very strong language, "...highest floods in 150 years... You're going to see hundreds of square miles under water..." In all, the advance information was very effective in mobilizing flood-fighting efforts throughout the basin.

All NWS offices should be encouraged to vigorously pursue notification of serious flood threats at the earliest possible time. Every NWS river forecast center should consider earlier release of flooding outlooks when conditions suggest a significant potential for spring flooding and when available data on snowpack conditions give high confidence that a serious flood threat exists. Decision-making on product release should also include consideration of how NWS outlook products are used and any intergovernmental actions which are triggered primarily by the outlook products' content.

Finding 11: The NCRFC and NWSO FGF recognized the potential for dangerous floods in the Red River of the North in 1997 well in advance and made a concerted and effective effort to advise action agencies and the public of the impending hazard.

Recommendation 11: NWS RFCs and offices with hydrologic service area responsibility should review this report as regards the potential for early coordination in response to heightened flood risks.

Forecast Service Overview

During the spring flood of 1997, 163 forecasts for above-record stage were issued by the NCRFC for the Red River of the North and its tributaries. The overall quality of NCRFC outlooks and forecasts was excellent although there were difficulties with the forecast services at three locations: East Grand Forks, Pembina, and Drayton:

Stage forecasts at East Grand Forks were raised from the 50-foot forecast value issued on April 14 in increments of 0.5 to 1.0 foot until the final crest forecast of 54 feet was issued on the evening of April 18 (see details in Appendix A). This "stair-stepping" contributed to decisions by those engaged in the flood fight to gear up to add "just one more foot" to the emergency levees until it was not possible to reallocate resources effectively to save critical facilities or higher elevation neighborhoods. The NWS raised these forecasts NOT because of revisions in the discharge forecast but because of the growing realization that the rating curve was inaccurate as the previous record stage was approached, then exceeded (see finding 1).

There has also been some criticism of NWS forecasts at Drayton and Pembina (downstream of East Grand Forks). Although these forecasts were raised in part as a reaction to the difficulties in the forecast situation at East Grand Forks, the increases primarily reflected a concern for the possibility of wind-induced waves. Wind had little effect on the crest stages at Drayton or Pembina (although such effects did occur downstream in Canada) so that ultimately these forecasts turned out to be too high.

NWS does not intentionally "stair-step" its flood forecasts, so a recommendation to simply avoid this would be useless. In a similar vein, the effects of wind on river stage are difficult to predict, so the addition of an allowance for wind-induced waves in a subjective fashion can be a reasonable forecast practice.

Staffing Considerations for Hydrologic Operations

The hydrology program at NWSO FGF has been developed effectively as a fully integrated station function even though the office is a recent spinup HSA office. NWSO FGF stringently applied the Central Region policy that all program manager positions (Warning Coordination Meteorologist (WCM), Service Hydrologist (SH), Meteorologist in Charge (MIC), Science and Operations Officer (SOO), and Data Acquisition Program Manager (DAPM)) are to be used primarily to meet their program management responsibilities. The MIC has a clear expectation that on-duty personnel should be able to handle duties every shift or utilize the standard call-back list if overwhelmed. As a result, all appropriate staff are trained and capable of gathering hydrologic data and issuing flood products. In this flood event, the MIC continued to abide by this policy for the most part, although the staff worked about 200 hours of overtime and/or compensatory time at FGF between March 31, 1997, and May 10, 1997. At the NCRFC, the duty time for the primary Red River of the North RFC forecasters was extended to include all the weekend periods through the flood.

NWS managers should give careful consideration to extending the duty hours of Service Hydrologists (SH) during major flooding episodes. This needs to balance multiple objectives including the need to have hydrologic services be a 24-hour station function at every WFO (i.e., not just a job for the SH), the desire to take advantage of the most highly skilled staff available during critical forecasting situations, the realistic limits on the number of hours an individual SH can be effective while on duty, the severity and duration of the flood event itself, and other operational demands. The survey team believes that MICs should consider extending the duty time of SHs when the supporting RFC goes into 24-hour operations as a result of flooding within their service area but considers the final judgement to be in the hands of the MIC, as is the case under current policies.

Diverse Interpretations of NWS Products

Overall, the NWS provided forecasts that were used successfully by communities in the Red River of the North Basin. It is clear, however, that forecast users, including the public, had very different interpretations of NWS products, especially as regards the uncertainty in those products.

In the interviews conducted by the Red River of the North survey team, different people interpreted the flood outlooks and forecasts of flood crests in different ways. Many users do not differentiate between outlooks and forecasts and view them as the same products, conveying similar levels of uncertainty.

NWS outlooks include two outlook peaks -- one (lower) outlook peak assuming no future precipitation and the other (higher) assuming normal precipitation. Both the language qualifying the higher outlook value and the historical experiences with past NWS outlooks indicate that the higher value is approximately a median; i.e., it has about 50 percent chance of being equaled or exceeded. (At East Grand Forks, the higher outlook value was equaled or exceeded in 6 of the 12 outlooks produced in 1980, 1982, 1984-1987, 1989, and 1993-1997.) In spite of the qualifying language and the historical performance of the outlooks themselves, many users interpreted the two flood crest levels issued in the outlook as a range; i.e., the two were viewed as minimum and maximum levels.

Moving from outlooks to forecasts, some viewed the flood crest forecast issued by the NWS as a maximum; i.e., a value that would not be exceeded. Others viewed the number as certain; still others viewed it as somewhat uncertain, with interviews revealing that the uncertainty in the forecasts is viewed to range from 2-10 percent of the predicted flood crest. The manner in which decision-makers interpreted the flood crest forecast affected the particular actions that they took in preparing for the flood. Consequently, it became obvious to the team that both the SENDING and RECEIVING of forecast stage information plays a critical role in preparing for and responding to floods, particularly floods at near-record or record levels where the stakes are high. It is also apparent to the team that the use and value of the EXISTING flood forecast products are not well understood, much less the potential improved usefulness and value that might be attained through adjusting the content of the products and manner in which they are delivered.

No common theme emerged in response to questions by the survey team regarding potential changes to NWS flood forecast products. Some users would like to be given a product that includes a range of possible crests; others want a single "best" estimate of the flood crest. Some would like a range but said they would only use the highest value. Some would like a range, but only if it were narrow; e.g., two-feet difference between the high and low value. Some would like a probability distribution; i.e., multiple values at various chances of exceedance.

Given the diversity of opinions within the survey team itself and the diversity of responses to questions regarding the format and content of NWS products, a fairly conservative approach to immediate changes in NWS services is indicated. The only specific change that can be recommended at this time is that NCRFC products should include both stage and discharge (not just stage) as an aid to improved coordination between the RFC and those users able to interpret discharge information (see Recommendations 7A and 7B).

Confidence and Uncertainty in NWS Products

NWS products and discussions by NWS staff generally included qualifications intended to convey the uncertainty inherent in NWS outlooks and forecasts. Nevertheless, many users developed a false sense of precision in NWS products. A number of factors helped contribute to this:

- Repetition of the outlook value (e.g., 49 feet at Grand Forks) contributed to an impression of certainty in that value. Due to the possibility of record flooding, the timing of the outlook issuance was changed by the NWS to include an earlier (February) numerical outlook. The earlier outlook had the positive impact of early mobilization of flood-fighting efforts, but it also extended the length of time that the same outlook value was cited. The March outlook value was identical (in value) to the February value, again extending the period when a single value was repeated. Finally, the blizzard event on April 5-6 delayed the start of the forecast production at East Grand Forks (the first forecast was issued on April 14 for a crest of 50 feet at East Grand Forks). During the period after the blizzard and before the April 14 forecast, the NWS continued to refer to the outlook value which had been provided in March. Again, repetition of the same outlook value contributed to a "locking in" by users on the outlook value of 49 feet at East Grand Forks.

- The numerical outlooks for Wahpeton, Fargo, and East Grand Forks were respectively 0.5, 0.16, and 0.2 foot above the historical record crest. In interviews with users, at least in the Grand Forks area, rather than elevating concern, the 49-foot outlook actually created a sense of complacency since it was only 0.2 foot over the record flood of 1979, which the city had survived. Many felt they were ready for the flood as forecast by the NWS. The high river stage in 1996 and subsequent successful flood fight (no damages) also contributed to this sense of confidence in 1997.

- The period after the blizzard of April 5 and 6 and before the issuance of the first operational forecasts on April 14 produced considerable confusion among NWS customers, including the general public. By repeatedly citing the flood potential outlook values produced before the blizzard, the NWS conveyed to many a high confidence in these numbers. Users expected that the forecast crest would increase immediately after the blizzard and generally did not understand that the period from April 6-14 was required to assess the impact of this blizzard on NWS forecasts.

NWS needs to study the methods used to convey the uncertain nature of its flood forecasts and outlooks. An analysis of the range of observed stages at particular discharge values based on historical discharge observations can help to establish a sense of the "inherent" uncertainty in stage forecasts at specific locations. Possibly, the addition of narrative information describing forecast difficulties; such as, the impact of the early April blizzard on data collection, may help users to assess forecast accuracy. The NWS needs to be as diligent as possible in guarding against over-confidence in the face of flood threats (or any other natural hazard) and be aware of the unintended message that repetition conveys increased confidence. A proactive approach to getting information out regarding the limits of forecasting accuracy needs to involve many forums: brochures, fact sheets, NWS products, flood or public information statements, contacts with the media, etc.

All of these concerns regarding conveying uncertainty in NWS forecasts are especially important for record and near-record events since there is little or no information available in the historical record regarding the actual behavior of the river / stream for the forecast.

Finding 12: NWS products and discussions by NWS staff generally included qualifications intended to convey the uncertainty inherent in NWS outlooks and forecasts. Nevertheless, many users developed a false sense of precision in NWS products.

Recommendation 12A: NWS RFCs and offices with hydrologic service area responsibility should review this report as regards the potential for misunderstanding the precision of NWS products.

Recommendation 12B: NCRFC should investigate estimating explicit exceedance probabilities for its current outlook products, based on an historical analysis of outlooks.

The NWS has conducted an Advanced Hydrologic Prediction System (AHPS) demonstration in the Des Moines area that can provide helpful information on forecast uncertainty. There are two main features of the AHPS demonstration that are important: The first is that AHPS technology offers the best means for the NWS to explicitly and objectively convey the uncertainty in NWS hydrologic forecasts. The second is that the interactive approach taken in the AHPS demonstration of surveying NWS customers for desired product changes, then, evaluating user acceptance of the new information is essential.

Finding 13: The Advanced Hydrologic Prediction System (AHPS) is the best means for the NWS to explicitly and objectively convey the uncertainty in NWS hydrologic forecasts.

Recommendation 13A: NWS should deploy AHPS capabilities Nationwide.

Recommendation 13B: Within the context of AHPS implementation, the NWS needs to work with users and apply their feedback to develop AHPS products that convey understandable information on the uncertain nature of river forecasts.

NWS OPERATIONS

Telephone Services

The NWS needs to ensure that all offices have adequate telephone lines to provide proper service during severe weather and flood events. The availability of telephone communications became an issue at both the NCRFC and NWSO FGF during the 1997 flood. NWS forecast offices were unable to reach the NCRFC on more than one occasion. Telephone communications were very nearly lost at the FGF office due to the threat that the flood itself would inundate the local telephone switching center. At one point at FGF, one line was inoperative; and another line was very noisy. The success of the service backup at FGF depended, in part, on the continued telephone service at FGF so that callers received a recording with instructions to call the backup site. Several parties (e.g., the USACE) mentioned the effectiveness of cellular phones during the flood fight but also noted some problems of overuse and attendant call blocking; the NWSO FGF also used cellular telephones.

Finding 14: Telephone services for the NCRFC and for FGF were critical to these offices during the 1997 flood. The number of lines available at NCRFC was inadequate, and telephone service at FGF was very nearly lost.

Recommendation 14A: The NWS regions should establish administrative procedures to assure that adequate phone services are available.

Recommendation 14B: The NWS should investigate the availability (and cost) of backup telephone services that might reroute calls around failed telephone switching systems.

Service Backup at Grand Forks Office

The transfer of service from and back to NWSO Eastern North Dakota appeared to go well from an external view. Within the agency, there was some minor confusion during the process regarding staff reassignments, but overall duties were performed very well. Transferred services were properly accomplished by the supporting NWS offices, especially NWSFO Bismarck. The fact that these offices only recently transferred aviation, public, and Hydrologic Service Area (HSA) responsibility to NWSO Eastern North Dakota contributed to this success.

The MIC at NWSO Eastern North Dakota attributes the success of the service backup, in part, to the gradual (i.e., one service area at a time) transfer of services from/to NWS offices; this should be considered in the event that service backup is needed in the future.

Impacts of the Flood on FGF

This event had a severe impact on the FGF office itself, both as regards the facility and as regards the staff. Positioning a sector facility technician at the FGF office was a great help in keeping the facility itself open and in avoiding damage to the facility during the time that service backup was initiated. About half of the staff had damage to their homes; one was a total loss. Yet, the staff continued to provide services to the public throughout the event. Policies on the use of leave by the staff in their personal recovery from the damage were liberalized, but the staff could have been supported in this area more quickly with a bit of foresight on the impact of the event of the staff. There are provisions for special assistance under the terms of the Employee Assistance Program (EAP) that could have been exercised to offer aid to the staff.

Finding 15: The NWS was well prepared for the impact of the flood event on the Eastern North Dakota NWSO facility but less prepared to offer aid to the NWS employees who were personally affected by the flood.

Recommendation 15: In any future event that has a widespread personal impact on the staff of an NWS office, the appropriate NWS Director should be prepared to aid the staff by (1) using the Employee Assistance Program to provide on-site support and (2) providing liberal leave to the extent possible.

NWS Staffing to Support Emergency Operations Centers

The staff resources of the NWS are quickly overtaxed during a major widespread disaster such as was experienced in the Red River of the North during April 1997. Emergency Operation Centers (EOCs) at Wahpeton, Grand Forks, and East Grand Forks were not staffed with NWS personnel during the Red River of the North flood. However, in discussions with the survey team, city and county emergency officials did not express a strong need to have NWS staff at the EOCs and felt they received adequate services via telephone, modem, and Internet communications. Certainly, computer communications make weather information available in a more user-friendly and timely manner than in the past; however, in-person service can extend beyond this and assist emergency managers in the decision-making process. Since EOC briefings often provide an opportunity for media contact, the lack of NWS representation also tends to reduce the media contact with the NWS. And local officials may have specific information of value to the NWS that will be conveyed more readily face-to-face. Impacts of overtime/compensatory time costs on NWS budget resources must also be considered.

The NWS needs to evaluate as an agency what level of staffing, if any, it can provide to city, county, and state EOCs, and what the needs of emergency managers are. Although NWS has limited staff to provide for EOC support on-site, there may be other creative approaches to temporarily provide increased EOC support for major flood events. The FEMA Reserves Program provides one model for this; for example, retired NWS staff could be temporarily hired to provide additional NWS staffing during major flood events.

Finding 16: A variety of opinions were expressed regarding the desirability of providing NWS staff support for city, county, and state Emergency Operations Centers.

Recommendation 16: The NWS needs to evaluate, as an agency, what level of staffing support, if any, it can provide to city, county, and state Emergency Operations Centers and identify possible alternate methods to meet these needs.

Coordination with Local Officials

Coordination with local officials involves exchange of information in both directions — provision of NWS forecasts and other data to local officials and the return of information from local officials on any local effects that might have an impact on river conditions and/or NWS forecasts. In general, this coordination activity was successful in both directions during this event. Nevertheless, there are a few issues regarding local coordination that deserve discussion. A great deal of interaction took place directly (by telephone) between the RFC hydrologists and city/county engineers and emergency services personnel in Wahpeton and Fargo, rather than via the forecast office in Grand Forks. Coordination with local officials in Grand Forks and East Grand Forks followed a different model, with the FGF office serving as an intermediary to the RFC. At times, city engineers and county emergency managers in Grand Forks and East Grand Forks had information and insight that might have facilitated the NWS flood forecasting effort but were so busy fighting the flood itself that this information was not relayed to the NWS. (The failure of the "plug" at the upstream end of Bygland Coulee discussed in the hydraulic analysis below is an example of potentially useful information that was not relayed to the NWS.) Considering the heavy work load at a river forecast center during a major flood and the pre-existing local contacts between NWS offices and the local officials in their service area, local forecast offices typically act as a primary path for the flow of information between local non-NWS entities and the NWS. However, the more direct contacts between the RFC and officials in Wahpeton and Fargo were effective in this event and are certainly acceptable practices within NWS policies.

Coordination with State Officials

The survey team reviewed the effectiveness of NWS coordination with state officials in North Dakota and in Minnesota. NWSFO Bismarck is the designated State Liaison Office for North Dakota. Ray Steiger, the Deputy Director of the North Dakota Department of Emergency Management (NDDEM), stated clearly that he would prefer to deal with only one NWS office, even when the event at hand involves more than one NWS office. This puts an extra emphasis on NWSFO Bismarck and NWSO Grand Forks to identify how Bismarck can best fulfill this role in providing service to NDDEM and other state agencies. Jim Franklin, Director of Minnesota Department of Emergency Management, also expressed a preference for a single point of contact but was not as strong in his statements and has been reaching out directly to the various NWS offices providing services to Minnesota.

Coordination with Federal Agencies

Real-time coordination among the Federal agencies supporting flood forecasting and flood-fighting activities in the Red River of the North floods of 1997 was exceptionally effective and was essential to the forecast process at NCRFC. The USGS was well aware of the potential for record flooding and had pre-positioned additional staff to take field observations of the event. These USGS field staff provided indispensable data to the NCRFC — not only the observations themselves, but also telephone conversations that helped to convey unusual flow conditions. Likewise, the field engineers of the USACE provided useful data and were in direct contact with the NCRFC.

The NCRFC could not confirm that it had copies of all the hydrologic analyses and studies that might be useful to support forecast procedures for all parts of its area of responsibility. NCRFC did have FEMA flood insurance studies but was not confident that they were all complete or up to date. NCRFC does generally get USACE project reports for projects that are actually built but not for proposed projects that are not built (as was the case for the Grand Forks USACE rating curve noted in media reports and discussed above). As-built Federal project reports include permanent levee descriptions, but temporary levees and levee modifications and locations are often not known to the RFC. The survey team believes it would be helpful to conduct a post-event technical session on the forecasting situation and all related technical matters among Federal agencies including FEMA, USACE, USGS, and the NWS. This meeting should confirm, in part, that the RFC has up-to-date information from these agencies. See also recommendation 1B above.

Finding 17: Other Federal agencies may have information in the form of flood studies, project investigations, etc., that could serve as reference materials to aid the NCRFC.

Recommendation 17: Conduct a post-event technical session on the forecasting situation and all related technical matters among Federal agencies including the FEMA, USACE, USGS, and the NWS (see also recommendation 1B).

Coordination with Canadian Officials

Coordination with Canadian officials occurred primarily with Alf Warkentin of the Water Resource Branch of the Manitoba Department of Natural Resources who felt coordination went very well for this event (and in general).

Finding 18: Coordination with Canadian officials occurred primarily with the Water Resource Branch of the Manitoba Department of Natural Resources who felt coordination went very well for this event (and in general).

Recommendation 18: To continue the effectiveness of coordination with Canada, appropriate Canadian officials should be invited to the technical sessions referred to in recommendations 1B and 17.

Local Electronic Dissemination

NWS dissemination methods are diverse and are undergoing significant changes, and it was apparent that the Grand Forks' staff has made an excellent effort to modernize their local dissemination methods. Methods available to NWS customers in the NWSO FGF service area included not only standard, nationally-supported NWS systems (Emergency Managers Weather Information Network (EMWIN), NOAA Weather Radio (NWR), etc.) but also effective local dissemination methods. NWSO FGF has implemented a hotline telephone, amateur radio links, a media telephone line, Internet, and a dial-in bulletin board service that emergency managers could use. At each news conference at NWSO FGF, the MIC described these sources to users. Some of these customers may still need help in making most effective use of these resources, but this can be dealt with effectively in the normal course of interactions between the FGF staff (primarily the WCM and the SH) in follow-up visits with NWS customers to ensure that they are able to access the information they need in the most efficient, possible way.

Handling Media Queries

The River Forecast Center HIC and the Grand Forks MIC did not have a clear agreement on how they would divide or refer media queries, at times creating frustration among themselves and their staffs over how to cope with media calls. Although MICs, HICs, WCMs, and SOOs receive media training in a managers' course at the NWS Training Center, Public Affairs officers in each NWS region need to work with the regions, river forecast centers, and local NWS field offices to develop more in-depth media training programs for field office managers and staff forecasters at WFOs and RFCs. The goals of the training should be to teach these staff members all of the necessary skills to efficiently and effectively respond to media queries in a severe event and to ensure that they get their key messages across in all interviews and public appearances as NWS spokespersons.

NWS field offices and river forecast centers should review their pre-season flood outreach practices and strive to contact editors at newspapers, television, and radio stations to identify key reporters who will most likely cover a potential flood event. If possible, the NWS offices should spend some time in workshops/briefings to educate reporters on NWS terminology and background and introduce them to key contacts within the NWS. Efforts should also be made to solicit feedback on clarity, quantity, and quality of information released by the NWS and use this information to improve and develop better communication tools and techniques for the future.

NWS headquarters should work with the regions to more clearly define the roles of the MIC, SH, and WCM in terms of who communicates flood-related information to the media during a major event. The WCM in Grand Forks did not have an active role in responding to flood-related media queries until after the flood struck the Grand Forks area, and the demands of the media increased significantly. Considering the increasing strain of coping with media queries during a major, protracted, flood event, using the WCM or other staff to coordinate responses to media queries and interview requests may be a practical method to balance the need to respond to media queries with other increased demands on the staff.

In short, there was no detailed media plan in place to help guide the MIC and HIC in effectively coping with and systematically responding to the large number of media queries on numerous subjects. In consultation with NWS headquarters Public Affairs, each NWS regional public affairs officer should coordinate "flood media plans" between NWS river forecast centers and forecast offices. Plans should identify responsibilities for responding to media queries, identify key local, regional, and national media contacts to receive all relevant NWS news releases, identify procedures for setting up a NWS media center, or procedures for providing NWS representation to a joint governmental media center, include copies of background information/fact sheets which can be used to quickly educate "out-of-town" and national/international reporters on unique local facts, outline a process for internally coordinating release of information, develop key messages/talking points for use by all involved NWS personnel and offices, and outline a decision tree for Public Affairs officers, MICs, and HICs to use in determining when they will likely need to have a regional Public Affairs officer or another NWS employee with media experience brought in to assist in managing media queries.

After the flooding around Grand Forks/East Grand Forks in mid-April, many news media reports focused on the controversy over the NWS outlooks and flood crest forecasts, rather than providing additional information about the ongoing flood event. Negative media reports surrounding the NWS forecasts for flood crests in the Grand Forks/East Grand Forks area had a significant impact on morale among personnel at both the Eastern North Dakota office and the North Central River Forecast Center. The NWS is accustomed to providing information on floods and other weather-related phenomenon to the media when the weather itself is the story. NWS field office staffs are less comfortable with dealings with the media when the NWS is the story. Media training and plans need to include dealing with those events when the focus of the story is the NWS itself.

Finding 19: The NCRFC HIC and the FGF MIC spent many hours providing interviews and other media responses, but they did not have a clear agreement on how they would manage media queries. While NWS Public Affairs Officers provided guidance and assistance during the flood event, there was no detailed media plan in place to help guide the MIC and HIC.

Recommendation 19A: Public Affairs officers in each NWS region should coordinate "flood media plans" between NWS river forecast centers and forecast offices.

Recommendation 19B: Public Affairs officers in each NWS region should develop and conduct media training sessions for NWS field offices.

APPENDIX A

Flood of 1997 at East Grand Forks, Minnesota

Time Table

2/6/97 - 2/9/97	Airborne snow survey of the Red River of the North conducted.
2/13/97	First Snowmelt Outlook issued using data from the airborne snow survey. The potential for spring flooding was characterized as "Severe" defined as levels at or exceeding the previous flood of record.
2/19/97 - 2/23/97	Airborne snow survey of the Red River of the North conducted.
2/20/97	USACE requested internal numerical flood crests. Decision to issue second Snowmelt Outlook in a numerical rather than categorical fashion was made and coordinated by the NWS.
2/24/97	Emergency managers notified that updated Snowmelt Outlook on 2/27/97 would be numerical.
2/27/97	Snowmelt Outlook updated. Outlook called for 47.5 feet with no additional precipitation and 49.0 feet with normal additional precipitation. The 49.0-foot forecast exceeded the existing flood of record that occurred on 4/26/79 (48.8 feet). Record numerical peak forecasts allowed the USACE to initiate advanced flood protection measures earlier than would otherwise have been possible.
3/6/97 - 3/12/97	Airborne snow survey of the Red River of the North conducted.
3/13/97	Snowmelt Outlook updated. No change from guidance issued on 2/27/97.
3/18/97 - 3/21/97	Airborne snow survey of the Red River of the North conducted.

3/23/97 - 3/27/97		Airborne snow survey of the Red River of the North conducted.
3/27/97		Snowmelt Outlook updated. No change from guidance issued on 3/13/97.
3/30/97		Flood Warning issued for all NWS river forecast points in the Red River of the North Basin.
4/3/97	1220	Current stage 18.1 feet. Forecast to continue to rise. Outlook with normal pcpn 49.0 feet. (Note that river model indicates that forecast peak may be well below the outlook peak of 49.0 feet, but forecasters were reluctant to lower the guidance).
4/4/97	1230	Current stage 23.6 feet. Forecast to rise to FS by 4/5. Outlook crest with normal pcpn 49.0 feet.
4/5-6		Severe blizzard conditions throughout Red River of the North. One to three inches of precipitation falls. Cold, windy, and snowy conditions hampered data collection and flood-fight activities.
4/5/97	1500	Current stage 28.4 feet. Outlook crest with normal pcpn 49.0 feet.
4/6/97	1330	Current stage estimated at 35.7 feet. Outlook crest 49.0 feet. (Note that since above normal precipitation had already occurred, the condition for the outlook crest was dropped.)
4/7/97	1400	Current stage 36.5 feet. Outlook crest 49.0 feet in mid- to late April.
4/8/97	1630	Current stage 38.8 feet. Outlook crest 49.0 feet in mid- to late April.
4/9/97	1210	Current stage 41.5 feet. Outlook crest 49.0 feet in mid- to late April.
4/9/97 - 4/12/97		Airborne snow survey of the Red River of the North conducted.
4/10/97	1300	Current stage 41.6 feet. Outlook crest 49.0 feet in mid- to late April

4/11/97	1230	Current stage 42.0 feet. Outlook crest 49.0 feet beginning 4th week of April.
4/12/97	1130	Current stage 42.3 feet. Outlook crest 49.0 feet beginning 4th week of April.
		(USGS measurements of flow indicate that ice effects are causing a 3.55-foot shift above the current rating curve).
		(Airborne snow survey completed.)
4/13/97	1110	Current stage 42.8 feet. Outlook crest 49.0 feet. This crest will be very broad, occurring as early as April 19, and extending as late as April 21-22.
		(Updated estimates of areal snow water equivalent delivered to the NCRFC for use in runoff model.)
4/14/97	1630	Current stage 43.7 feet. Crest 50.0 feet - April 19-22. (Note this is the first non-outlook crest forecast for East Grand Forks).
4/14/97 - 4/17/97		Airborne snow survey of the Red River of the North conducted.
4/15/97	1330	Current stage 45.3 feet. Crest 50.0 feet - April 22-23.
4/15/97	2134	Current stage 46.4 feet. Crest 50.0 feet - April 22-23.
		(USGS measurements of flow indicate ice effects are causing a 1.44-foot shift above the current rating curve).
4/16/97	0950	Current stage 47.5 feet. Rise to 49.0 to 49.5 feet - April 17, then slow rise to 50.0 feet April 22-23.
		(USACE field construction personnel alerted to raise emergency flood protection by raising top of the levee to a stage of 54.0 feet.)
4/16/97	1620	1600 stage 48.4 feet. Rise to 49.5 feet by early April 17, then continue rise to crest of 50.0 to 50.5 feet - April 20-22.

4/16/97	2120	Current stage 48.8 feet. Rise to near 49.5 feet early on April 17, then continue rise to crest of 50.0 to 50.5 feet - April 20-22.
		(USGS measurements of flow indicate a 0.94-foot shift above the current rating curve).
4/17/97	1215	Current stage 49.6 feet. Crest 50.0 to 50.5 feet April 18 p.m. - April 19 a.m.
		(USACE contracts for additional resources to raise levees).
4/17/97	2125	Current stage 50.9 feet. Crest 51.5 - 52.0 feet - April 18; April 19. Ice effects in the area appear to be causing fluctuations in the rate of rise.
4/18/97	0905	Current stage 52.0 feet. Crest 53.0 ft April 18-19.
		(Severe seepage and boils behind levees in Belmont Park, Lincoln Park, and Central Park areas of Grand Forks with similar problems in East Grand Forks.)
		(Sandbag levee on the Point in East Grand Forks breached allowing inundation of the Point area, following failure of efforts to shore up the levee.)
		(Numerous levee failures occurred on both sides of the river. USACE reported that all levee breeches and over-toppings appear to have occurred between river stages of 51.6 and 53.0 feet.)
4/18/97	1950	1900 stage 52.6 feet. Crest near 54.0 feet late Saturday (April 19).
4/19/97	0945	0500 stage 52.9 feet. Little change next few days - additional rises of 0.2 to 0.3 foot are possible.
		(Fire broke out in Grand Forks and destroyed 11 buildings).
4/19/97	1510	1200 stage 53.1 feet. Rise to near 54.0 feet over the next few days.
4/19/97	2010	1800 stage 53.3 feet. Slow rise to near 54.0 feet next few days.

4/20/97	1135	Current stage 53.7 feet. Crest 54.0 ft - April 21. Fluctuations of 0.1 to 0.3 feet are possible.
		(Hydrologic Service Area (HSA) responsibility transferred from NWSO FGF to NWSFO BIS)
4/20/97	2106	Current stage 53.9 feet. Crest 54.0 feet - 4/21. Fluctuations of 0.1 to 0.3 ft are possible.
4/21/97	1235	Current stage 53.9 feet. Near crest; remain near this level for several days. Fluctuations of 0.1 to 0.3 foot are possible.
4/21/97	2130	Estimated stage 54.0 feet. Near crest; remain near this level for several days.
4/22/97	1130	Estimated stage 54.0 feet. Cresting; little change next 24-48 hours.
4/22/97	2119	Current stage 53.8 feet. Cresting; little change next 24-48 hours.
4/23/97	1010	Current stage 53.6 feet. Continue very slow fall next several days.
4/23/97	2116	1600 stage 53.2 feet. Continue very slow fall next several days.
4/24/97	1000	Current stage 52.6 feet. Fall to 51.0 feet by late April 25. Fall to 50.0 feet by 4.27. 0.1 to 0.3 foot surges in stage are possible.
4/24/97	2118	Estimated stage 52.0 feet. Fall to 51.0 feet by late April 25. Fall to 50.0 feet by 4.27. 0.1 to 0.3 foot surges in stage are possible.
4/25/97	1045	Stage missing. Slow fall.
4/25/97	2124	Current stage 50.5 feet. Continue slow fall.
4/26/97	0945	Current stage 49.7 feet. 3-day forecast: 48.0/46.8/45.9 feet.
4/26/97	2124	Current stage 49.1 feet. 3-day forecast: 48.3/47.2/46.3 feet.
4/27/97	0935	Current stage 48.2 feet. 3-day forecast: 47.0/45.8/44.3 feet.

4/27/97	2142	Current stage 47.6 feet. 3-day forecast: 47.1/46.0/45.3 feet.
4/28/97	0935	Current stage 46.9 feet. 3-day forecast: 46.0/44.6/43.2 feet.
4/28/97	2118	Current stage 46.4 feet. 3-day forecast: 46.0/44.6/43.2 feet.
4/29/97	1045	Estimated stage 46.2 feet. 3-day forecast: 45.5/44.8/44.4 feet.
4/29/97	2119	Current stage 45.3 feet. 3-day forecast: 45.0/44.5/44.1 feet.
4/30/97	0915	Current stage 44.8 feet. 3-day forecast: 43.9/42.7/41.5 feet.
5/01/97	1005	Estimated stage 43.9 feet. 3-day forecast: 43.0/42.1/41.2 feet.
5/02/97	1025	Current stage 43.8 feet. 3-day forecast: 43.0/42.2/41.4 feet. Continued slow fall.

APPENDIX B

Hydraulic Analysis in the Grand Forks Vicinity

The results of an hydraulic modeling analysis of the Red River of the North in the area of Grand Forks, North Dakota, and East Grand Forks, Minnesota are presented in this appendix. Some hydraulic conditions were not accounted for in the NWS forecast. The purpose of the analysis was to determine the effects of the hydraulic conditions of the record flood of 1997 on the gage at Grand Forks.

Hydrographs Used in Hydraulic Analysis

On the evening of April 16, 1997, the NWS issued a forecast for a crest stage of 50.0-50.5 feet at the East Grand Forks, Minnesota, gage (mi 297.65). (See Appendix A for details.) The peak stage was expected to occur April 20-22. A discharge of ~110,000 cfs was expected to coincide with the forecast peak stage. The observed peak stage at East Grand Forks occurred on April 22 and had a value of 54.35 feet. A peak discharge of 137,000 cfs (adjusted from an original USGS estimate of 151,000 cfs) occurred on April 18. Figure B-1 shows the stage hydrograph observed by the USGS and the peak stage forecast which underestimated the peak stage by ~3.8 feet.

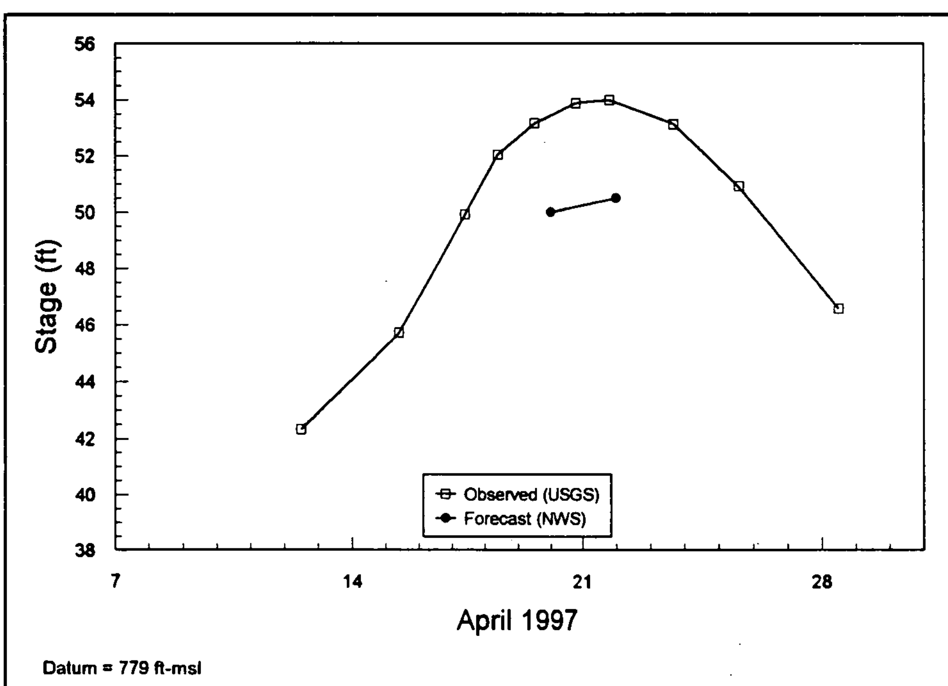

Figure B-1. USGS Observed Stage Hydrograph vs. NWS Stage Forecast, East Grand Forks, MN.

Figure B-2 shows the discharge hydrograph observed by the USGS as well as the discharge hydrograph simulated by the NWS on April 24, 1997. (This analysis used the April 24 hydrograph, but the simulated hydrograph by the NWS changed minimally between April 16 and April 24.) Although the peak observed discharge (which occurred before the peak stage) was not captured in the NWS simulation (Figure B-2), the discharge (114,000 cfs) which did occur during the peak stage was close to the simulated value.

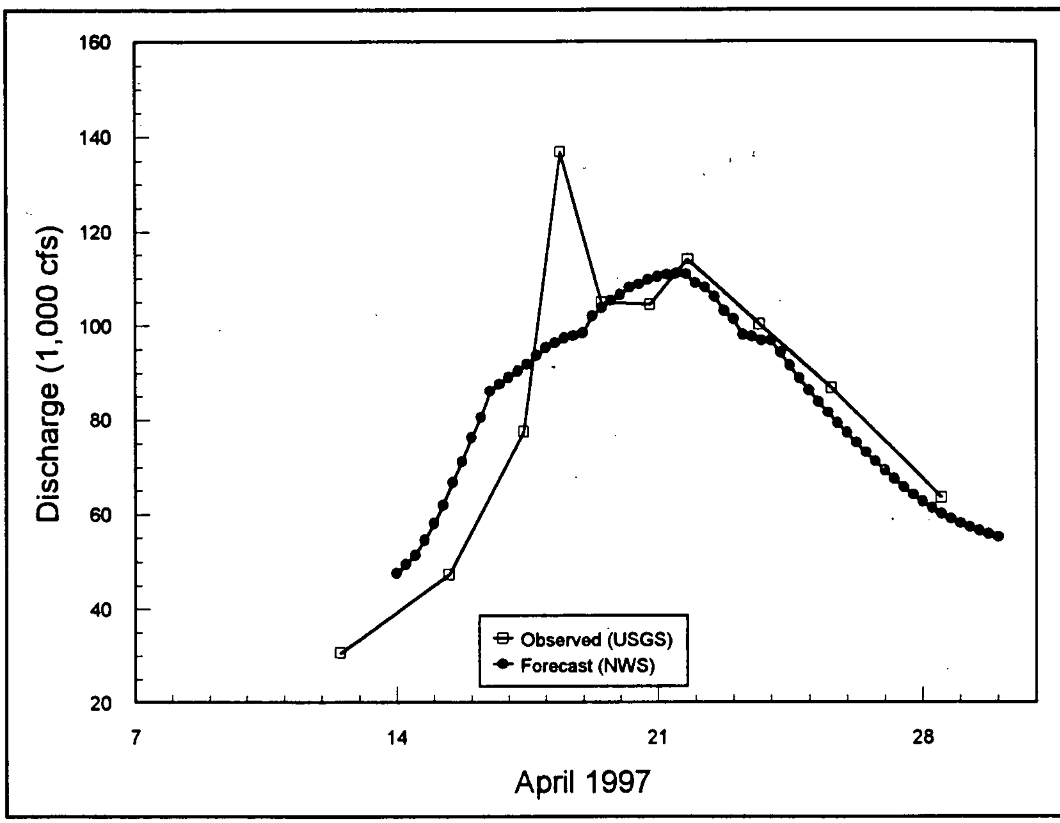

Figure B-2. Observed vs. Forecast Hydrograph, East Grand Forks, MN.

Extent of Study Area

Figure B-3 shows the extent of the Red River of the North Basin considered in this analysis. The analysis was done in two parts.

Figure B-3 - Red River of the North River System.

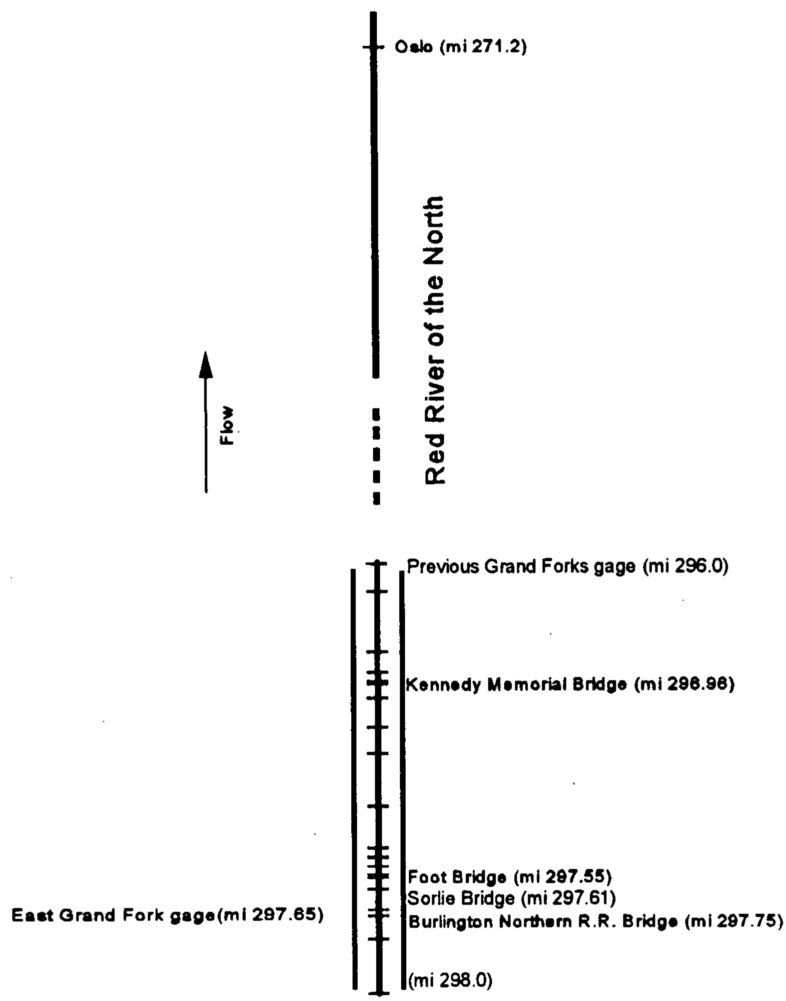

Figure B-4 - Schematic of the Red River of the North Study Reach.

The first part of the study relates to the peak stage at the East Grand Forks gage. The particular reach of the Red River of the North studied in the first part of the analysis is 26.8 miles long. It begins immediately downstream of the confluence of the Red Lake River with the Red River of the North (mi 298.0) which is just upstream of Grand Forks and extends downstream to Oslo, Minnesota, (mi 271.2) as shown in Figure B-4. There are four bridges in the study reach within two miles of the Grand Forks gage (mi 297.65). During the 1997 flood, the natural earthen levees on both sides of the river were temporarily raised with sandbags for the first two miles of the study reach. These bridges and levees may have caused an increase in the flood crest. In addition to the bridges and levees, the Red River of the North has a very mild slope (~0.5 ft/mi in the Grand Forks area and ~0.2 ft/mi for the greater portion of the reach extending downstream of the Grand Forks area). Such extremely mild gradients may have caused the river to experience backwater effects. Although the Red River of the North during high flows is fairly wide (~5 miles at the end of the study reach), in the Grand Forks area, the channel is naturally constricted, measuring only 600 feet wide at some locations even during peak flood flows. This also may have caused backwater effects.

The second part of the analysis relates to the peak discharge at the East Grand Forks gage. There was a "plug" on the Red River of the North 19.2 miles above its confluence with the Red Lake River which "blew out" and allowed water to leave the Red River of the North prematurely and flow through the Bygland Coulee (a 12-mile drainage channel) into the Red Lake River 1.9 miles above its confluence with the Red River of the North (Figure B-5). This coulee flow was speculated by some to have increased the peak flow at East Grand Forks. A sensitivity analysis was done to determine the effect of the coulee outbreak on the peak discharge at East Grand Forks.

Model Calibration Results

The effects of the above hydraulic conditions (except for the coulee outbreak) on the Red River of the North in the Grand Forks area were analyzed using the NWS FLDWAV model which is a one-dimensional, dynamic routing model that utilizes the complete St. Venant equations of unsteady flow. FLDWAV simultaneously solved for the water level (h) and the discharge (Q) at 52 selected cross-sections located along the study reach (from immediately below the Red Lake River-Red River of the North confluence to Oslo, Minnesota) for each time interval during the specified simulation time period. FLDWAV utilized the following information in the simulation: an upstream boundary condition of known (measured) discharge time series; a downstream boundary condition of measured stage time series; cross-section properties; hydraulic roughness coefficients which vary with Q; and information describing the hydraulic effects of each of the four bridges. For this analysis, FLDWAV used calibrated hydraulic roughness coefficients.

The time period of the analysis was April 9-27, 1997. Stage measurements (Figure B-1) and discharge measurements (Figure B-2) were taken by the USGS throughout the flood period.

Stage measurements were taken at the East Grand Forks gage (mi 297.65). A maximum stage of 54.35 feet was measured on April 22. Discharge measurements were taken at the Sorlie Bridge (mi 297.61) until April 18 when a flow of 137,000 cfs (adjusted from an original USGS estimate of 151,000 cfs) was measured within the levees. On April 19, levees were overtopped/breached; and subsequent discharge measurements were taken at the Kennedy Bridge (mi 296.96). For the first part of the analysis, the upstream boundary condition (mi 298.0) was a discharge hydrograph (Figure B-6) based on the USGS measurements at East Grand Forks/Kennedy Bridge; and the downstream boundary (mi 271.2) was a stage hydrograph at Oslo, Minnesota (Figure B-7). The 52 cross-sections which describe the study reach were obtained from the U.S. Army Corps of Engineers (USACE).

The model results were compared with the observed stage hydrograph at the East Grand Forks gage (Figure B-8). Although FLDWAV had difficulty modeling the stages at or near the peak flow (maximum stage error of 1.8 feet), the peak stage (54.0 feet) simulated by FLDWAV which occurred approximately 18 hours after the peak flow was very close to the observed value (54.35 feet). The simulated peak water surface profile plotted against several observed high water marks along the study reach between the upstream boundary (mi 298.0) and the previous Grand Forks gage location (mi 296.0) are shown in Figure B-9. The simulated peak stages were within ~0.3 feet of the observed values, except at the Sorlie Bridge where the simulated peak stage was within ~0.6 feet of the observed value. A comparison between the observed and simulated stage-discharge relationship (rating curve) at East Grand Forks was also made. As shown in Figure B-10, the simulated rating curve matched the measured rating curve fairly well, especially at the peak stage.

Flood Forecast Results

As stated previously, the NWS forecast on April 16, 1997, a peak stage of ~50.5 ft at the East Grand Forks gage (mi 297.65) with a discharge of 110,000 cfs to occur on April 20-22. The observed peak stage at East Grand Forks was 54.35 feet on April 22. The peak stage was under-forecast by ~3.8 feet. Two primary factors contributed to the error in the stage forecast: (1) the difference between the forecast discharge hydrograph and the actual discharge hydrograph and (2) the difference between the rating curve used to produce the forecast stage and the actual rating curve for the event. Since FLDWAV was able to adequately simulate the 1997 flood event with its many complexities (e.g., bridges, levees, backwater), the results of the simulation will be used to determine how the discharge hydrograph and the rating curve affected the peak stage at the East Grand Forks gage.

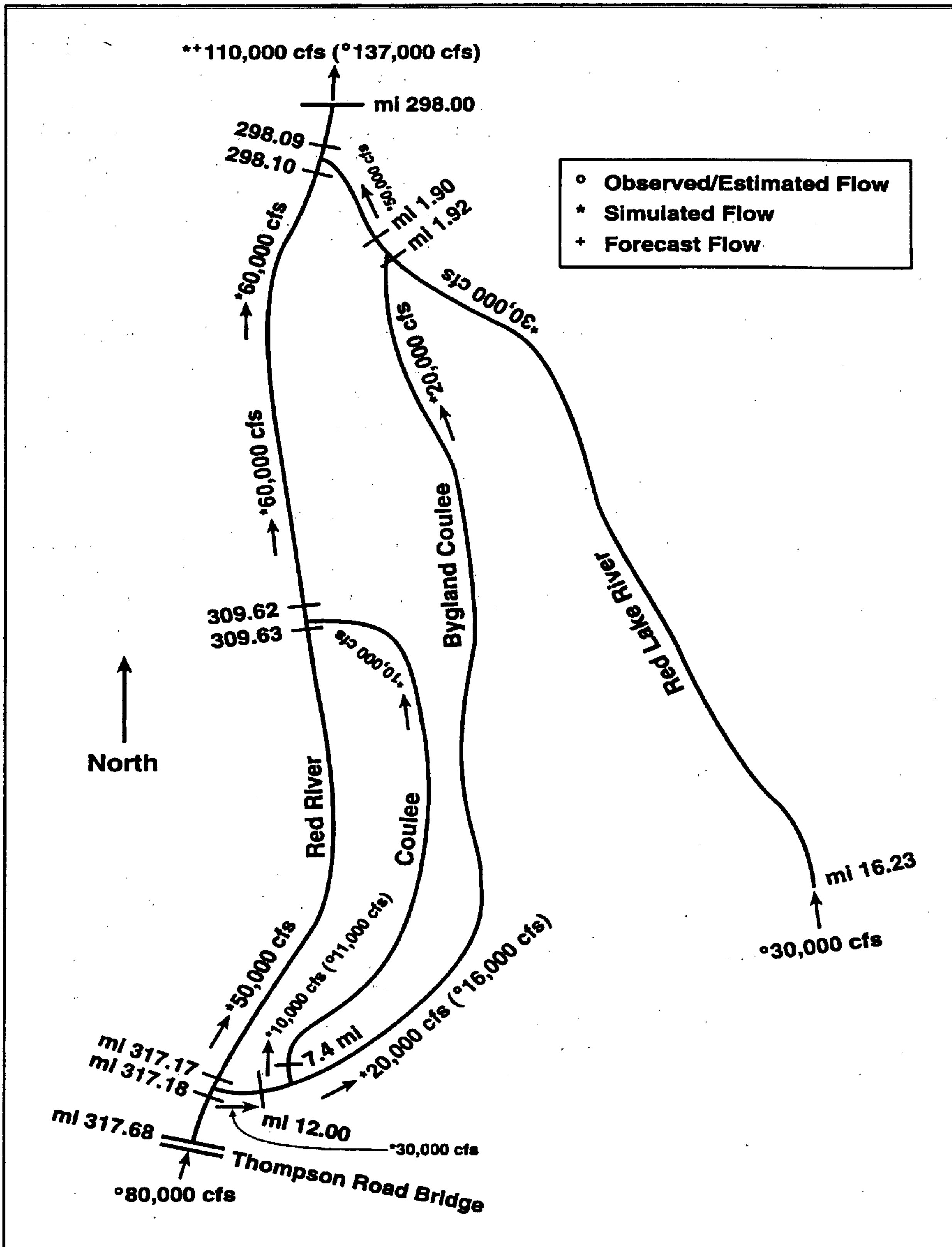

Figure B-5. Schematic of Red River of the North-Coulee-Red Lake River System

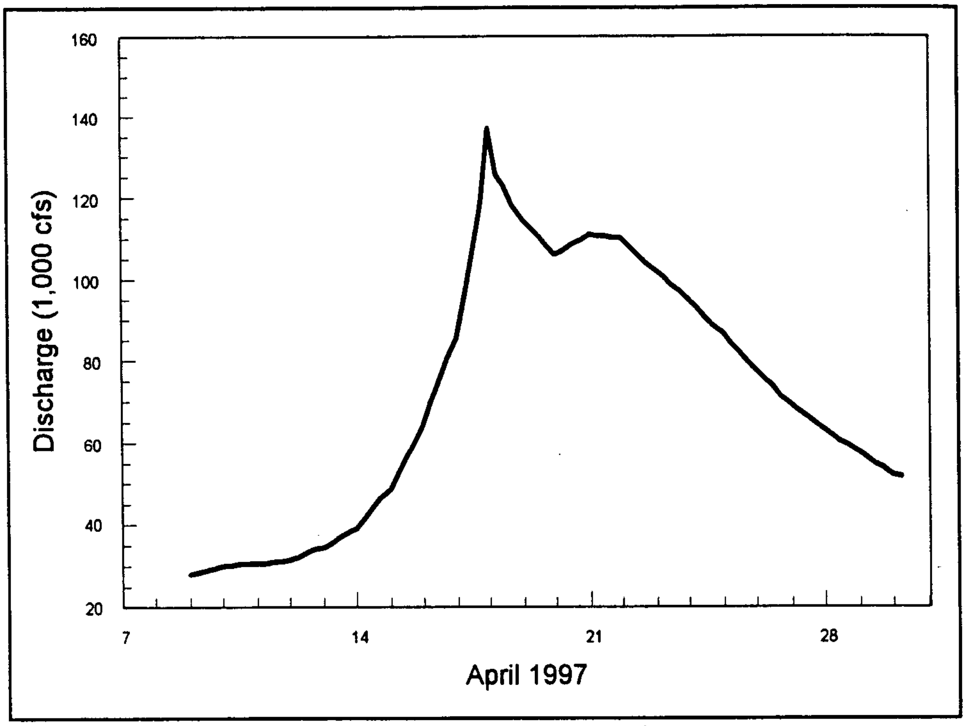

Figure B-6. Upstream Boundary: Discharge Hydrograph at East Grand Forks, MN.

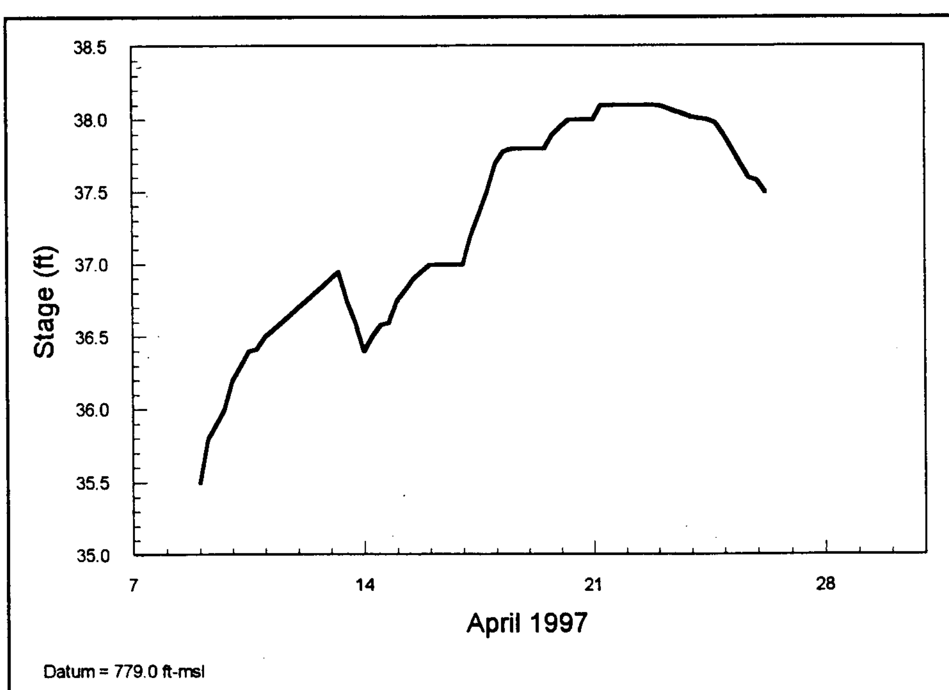

Figure B-7. Downstream Boundary: Stage Hydrograph at Oslo, MN.

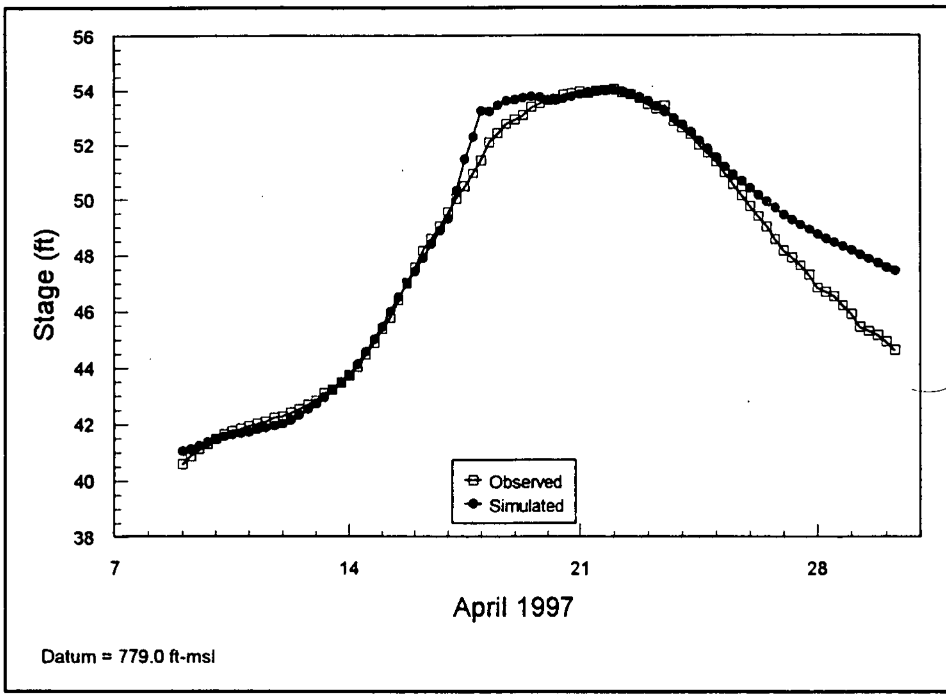

Figure B-8. Simulated vs. Observed Stage Hydrograph at East Grand Forks, MN.

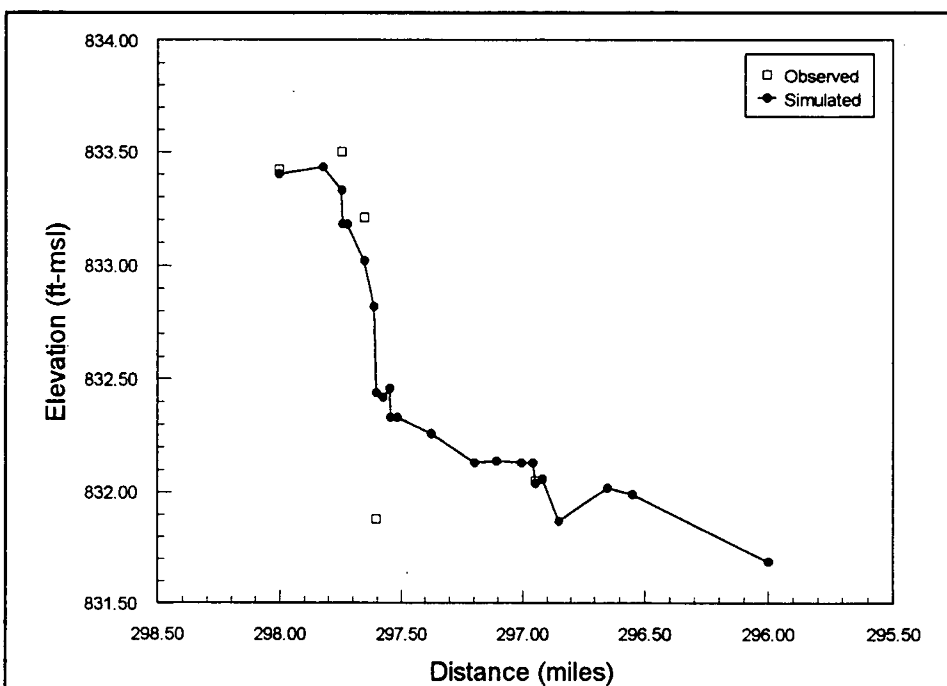

Figure B-9. Peak Water Surface Profile, Red River of the North (Observations from High Water Marks).

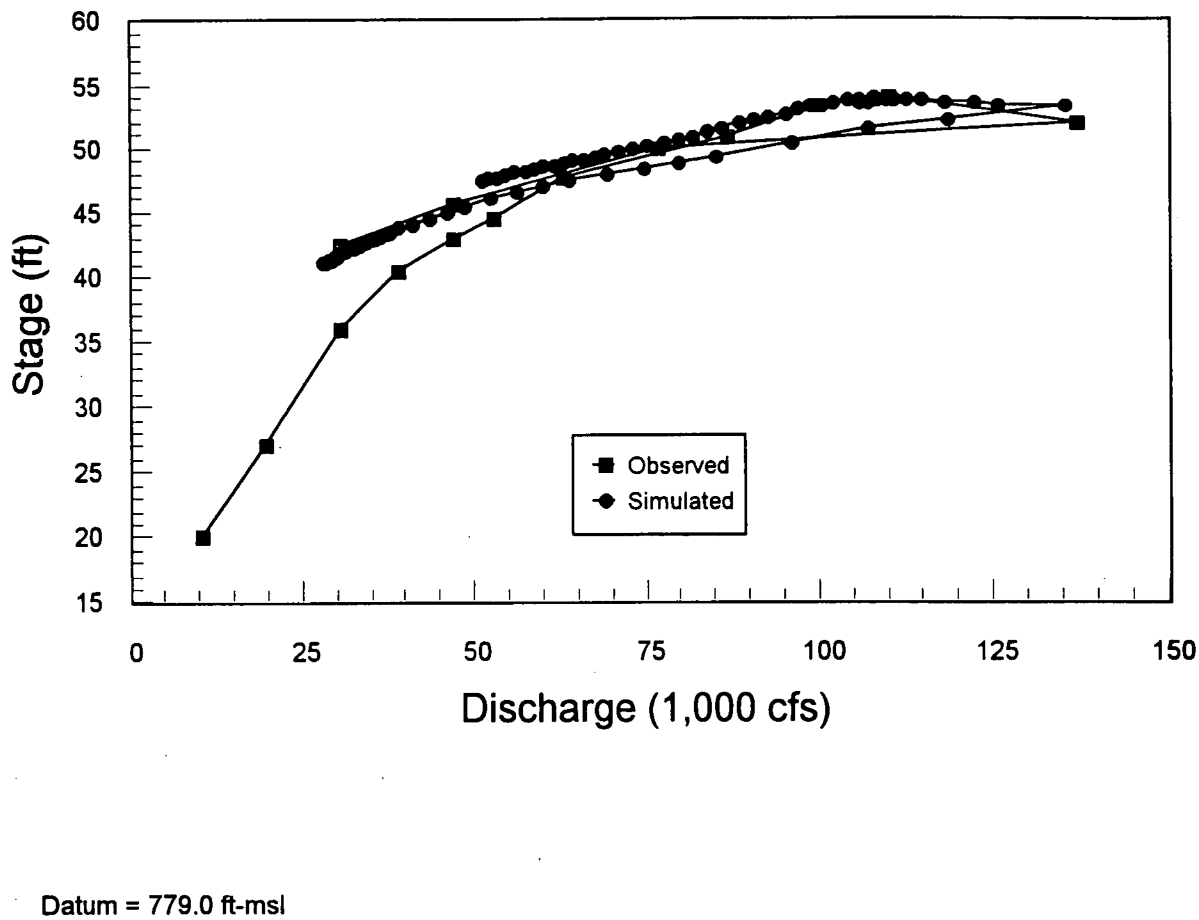

Figure B-10. Simulated vs. Observed Rating Curves at East Grand Forks, MN

Effects of Discharge Hydrograph on Stages Produced by FLDWAV

The NWS uses hydrologic models to generate discharge hydrographs (headwater runoff) in headwater basins and storage routing techniques to route the discharge hydrographs downstream. The hydrologic models also generate discharge hydrographs (local runoff) in sub-basins located adjacent to the river through which the routed flow is passing. The combined local runoff and routed flow are later adjusted based on observed flow data. A rating curve is then used to convert the forecast discharges into stage values.

A comparison (Figure B-2) was made between the discharge hydrograph measured by the USGS and the hydrograph forecast by NWS at East Grand Forks (mi 297.65). The 1997 flood, as measured by the USGS, was a double-peak flow event; the first and larger peak occurred on April 18; and the second peak occurred on April 22. The NWS forecast hydrograph captured the second peak flow which was also when the peak stage (54.35 feet) occurred; however, it was not able to capture the first peak flow. This inability may have resulted from local inflow not being represented by the NWS hydrologic model; or it may have resulted from upstream hydrographs that, likewise, failed to include the first discharge peak; however, it is not within the scope of this analysis to determine the source of the error in discharge.

To determine the effect of the discharge hydrograph on the peak stage at East Grand Forks, the FLDWAV model was run with the NWS forecast hydrograph replacing the USGS-measured hydrograph as inflow to the model. As shown in Figure B-11, the peak stage (53.9 feet) produced by FLDWAV (using NWS forecast inflow) which occurred on April 22 was less than the observed stage (54.35 feet) by ~0.4 foot. When comparing the peak water surface profiles (Figure B-12), the profile generated using the NWS forecast inflow produced peak stages about 0.2 foot less than the peak stages in the profile generated using the USGS-measured inflow. Effects of the two discharge hydrographs on the relation between discharges and stages (rating curve) were also analyzed. The rating curve produced by FLDWAV using the NWS forecast inflow hydrograph was compared with the observed "looped" rating curve (Figure B-13). Although the rising limb of the FLDWAV-generated rating curve produced higher stages than were observed, the recession limb of the rating curve (including the peak) matched the observed rating curve very well.

Effects of Rating Curves on Stages Produced by FLDWAV

One of the critical tools used in river forecasting is an empirical (observed from previous floods) rating curve which describes the relationship between discharge (Q) and stage (h); this relationship is unique for a particular location along the river; and it may change with time due to changes in the river cross-section at the location of the rating curve; it is updated using measurements taken by the USGS. Although adequate for most rivers, such an empirical rating curve is single-valued (i.e., one-to-one relationship between h and Q) and may not reflect the hydraulic conditions in the river system (e.g., backwater due to very mild river bottom slopes (< 1 ft/mi - such backwater effects become more significant as the river slope approaches zero)). In such rivers, the water-surface elevation tends to be higher on the falling limb of the hydrograph than on the rising limb at the same discharge; this situation produces a "looped" rating curve. The band-width of the loop can range from a few inches to several feet depending on the hydraulic conditions (i.e., primarily, the slope of the river profile and the rate of rise of the hydrograph). The magnitude of the loop increases as the slope decreases and as the rate of rise increases. The rating curve measured by the USGS at the East Grand Forks gage (Figure B-10) shows this looping effect; the band-width of the loop is 2.8 feet. The hydraulic effects which contribute to the loop will be discussed later. As stated previously, the rating curve generated by the FLDWAV model matched the measured rating curve fairly well especially at the peak stage (Figure B-10).

The USGS periodically issues a single-valued rating curve based on observed data. The NWS uses this empirical rating curve to forecast stages for real-time floods. When forecasting peak stages that go beyond the flood of record, the rating curve must be extended (extrapolated) to greater

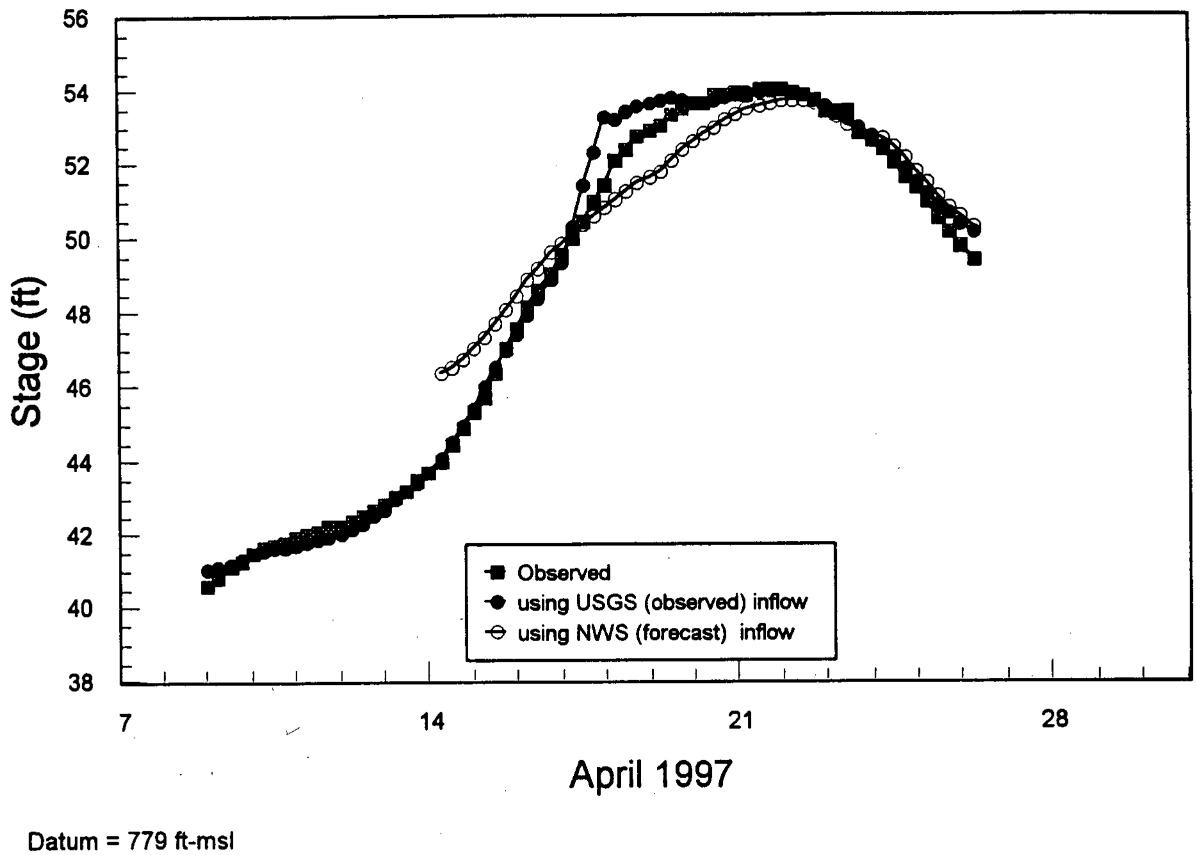

Figure B-11. Stage Hydrographs at East Grand Forks, MN (Inflow Comparison).

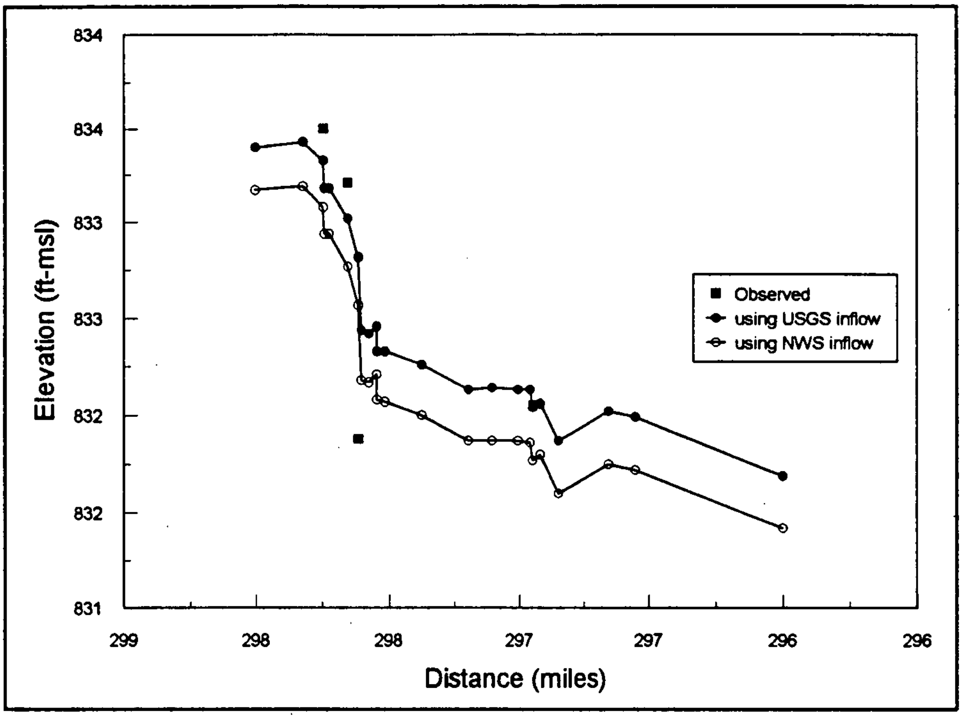

Figure B-12. Water Surface Profile (Inflow Comparison).

discharges and corresponding stages. Although the extrapolation technique may account for some of the hydraulic effects which are included in the empirical rating curve, hydraulic conditions may change as the flow increases and cause the rating curve to change in an unanticipated manner. During the 1997 flood event, the USGS Rating Curve No. 18 at East Grand Forks was used; however, it was extended along the same slope as the known curve using a logarithmic extrapolation technique. When compared with the FLDWAV- generated loop rating curve, Figure B-13 indicates that the extended rating curve is able to match the rising limb of the FLDWAV-generated rating curve; however, it cannot account for the looping effect. At the peak discharge (137,000 cfs) which occurs on the rising limb, the corresponding stage using the USGS-NWS extended rating curve is 51.9 feet which compares very closely to the observed stage (52.0 feet) at this flow (although FLDWAV produced a value of 53.3 feet). The peak stage occurs on the recession limb at 110,000 cfs for which the USGS-NWS extended rating curve produced a stage value of 50.5 feet compared to the observed stage of 54.35 feet. Prior to the 1997 flood event and in the course of performing an hydraulic design project, the USACE generated a single-valued rating curve (Figure B-13) which took into account some hydraulic effects (e.g., bridges). Although this USACE rating curve is unable to adequately represent the rising limb (e.g. it shows 57.0 feet at 137,000 cfs compared to the observed 52.0 feet), it represents the falling limb quite well especially at the peak stage (54.0 ft at 110,000 cfs).

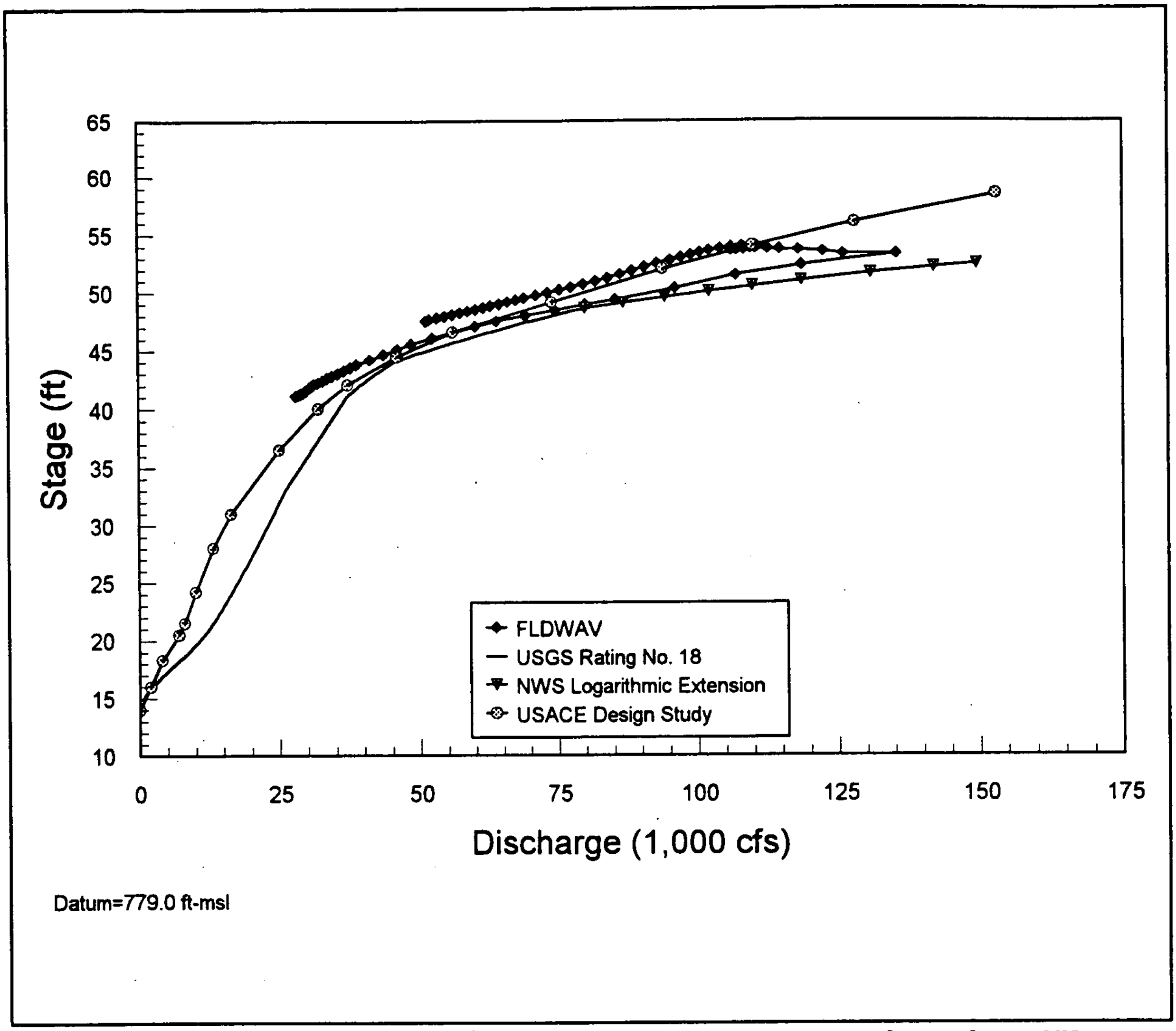

Figure B-13. Computed Rating Curves at East Grand Forks, MN.

Hydraulic Effects

The shape of the rating curve including the looping effect (mathematically, this is called hysteresis) was caused by hydraulic conditions including bridges, levees, and backwater due to the very mild slope downstream of Grand Forks. The effects of the bridges and levees are analyzed below.

Effect of Bridges on Stages at the East Grand Forks Gage

Bridges usually cause the flow in a river to be constricted since the cross-section at the bridge is usually narrower than the cross-sections of the natural channel; bridge piers further constrict the section. Channel constrictions cause some amount of backwater effect. Bridge decks may also affect the channel flow. As long as the water flows beneath the bottom of the bridge deck, the flow is less restricted (influenced only by the bridge piers and the width of the cross-section where the bridge is located); however, once the water impinges on the bridge deck, the flow is subjected to greater friction leading to a greater head loss which requires a higher water-surface elevation immediately upstream of the bridge to pass the given discharge. Road embankments crossing the flood plain and connected to the bridge also constrict the flow which overtops the banks of the cross-section. If the water level reaches the top of the road embankment, water can also flow over the road embankment as weir-type flow.

To determine the effects of the bridge components, the FLDWAV model was run with the following scenarios: 1) all four bridges were removed from the system; 2) all of the bridges were added without the bridge decks or embankments to determine the effect of the bridge constrictions; 3) the embankments were added and weir flow was allowed over the road embankments; and 4) the bridge decks were added to create additional head losses for the highest water level conditions. It can be seen in Table B-1 that the dominant component is the bridge constriction which resulted in 0.66 foot increase at the peak elevation. Allowing flow over the embankments caused the peak elevation to be reduced by 0.19 foot. The bridge decks further increase the peak elevation 0.31 foot. It was found that the overall effect of the four bridges on the East Grand Forks gage resulted in an increase in the water-surface elevation of 0.78 foot. Figure B-14 shows the rating curve at the East Grand Forks gage for the four scenarios along with the USGS-NWS extended rating curve used in the NWS forecast. It can be seen that the single-valued rating curve tends to behave like the "no bridges" scenario.

Table B-1. Effect of Bridge Components on the East Grand Forks Gage (mi 297.65).

	Peak Elevation *(feet-msl)*	**Peak Stage** *(feet)*	**Total Difference** *(feet)*	**Individual Effect** *(feet)*
All Bridges Neglected	832.28	53.28	-----	
All Bridges Included (No Decks or Embankment Overflows) --Effect of Bridge Constrictions	832.94	53.94	+0.66	+0.66
All Bridges Included (No Decks) --Effect of Embankment Overflow	832.75	53.75	+0.47	-0.19
All Bridges Included (As Built) --Effect of Bridge Decks	833.06	54.06	+0.78	+0.31
Overall Bridge Effects				**+0.78**

An analysis was also done to determine the individual effect of each bridge. The FLDWAV model was run four times to reflect the elimination of each individual bridge. Table B-2 shows that the most critical bridges in the system were the Sorlie Bridge (mi 297.61) with an increase in head of 0.44 foot and the Foot Bridge (mi 297.55) with an increase in head of 0.25 foot. The Burlington R.R. Bridge (mi 297.75) and Kennedy Bridge (296.96) had minimal effect on the peak stage at the East Grand Forks gage. The peak stage profile of each scenario is shown in Figure B-15.

Table B-2. Effect of Each Individual Bridge on the East Grand Forks Gage (mi 297.65).

Bridges Included in the FLDWAV Run	**Location** *(mi)*	**Peak Elevation** *(feet-msl)*	**Peak Stage** *(feet)*	**Difference** *(feet)*
All Bridges		833.06	54.06	-----
All Bridges except Burlington R.R. Bridge	297.75	833.06	54.06	0.00
All Bridges except Sorlie Bridge	297.61	832.62	53.62	0.44
All Bridges except Foot Bridge	297.55	832.81	53.81	0.25
All Bridges except Kennedy Bridge	296.96	832.97	53.97	0.09

Effect of Levee Overtopping on Stages at East Grand Forks Gage

Levees, located along the banks of a river, tend to produce higher water levels than if the river were not leveed. In the study reach, the levees extend from mi 298.0 (the upstream end of the study reach) to mi 296.55 (approximately one mile downstream of the East Grand Forks gage). To determine the effect of the levees on the Red River of the North in the study reach, two simulations using FLDWAV were made. In the first simulation, the levees were allowed to overtop at the estimated levee top elevations including the temporary addition of sandbags (831.6 feet above mean sea level (msl)). In the second simulation, the levees were extended sufficiently upward such that no overtopping would occur. The second simulation, when compared to the first, provides the means to understand the effect of the levee overtopping. As shown in Figure B-16, the levees had minimal effect on the peak stage at the East Grand Forks gage. Overtopping of the levees caused a reduction in stage of 0.04 foot at the East Grand Forks gage. This indicates that the overbank storage volume behind the levees had minimal effect on the peak stage in this flood.

Effect of Coulee Outbreak on Peak Discharge at East Grand Forks Gage

There was an outbreak of flow from the Red River of the North at mi 317.18 (~19.2 miles above its confluence with the Red Lake River) into two coulees: the Bygland Coulee which is 12 miles long and connects into the Red Lake River 1.9 miles above the Red River of the North-Red Lake River confluence; and a secondary coulee which is 7.4 miles long and connects back into the Red River of the North 11.5 miles above the Red River of the North-Red Lake River confluence. The peak flow on the Red River of the North at Halstad, Minnesota, (mi 375.2) was 80,000 cfs; and the peak flow on the Red Lake River at Crookston, Minnesota, (mi 52.2) was 30,000 cfs. After the flood, estimated peak flows (based on the slope-area method) were computed as 16,000 cfs in

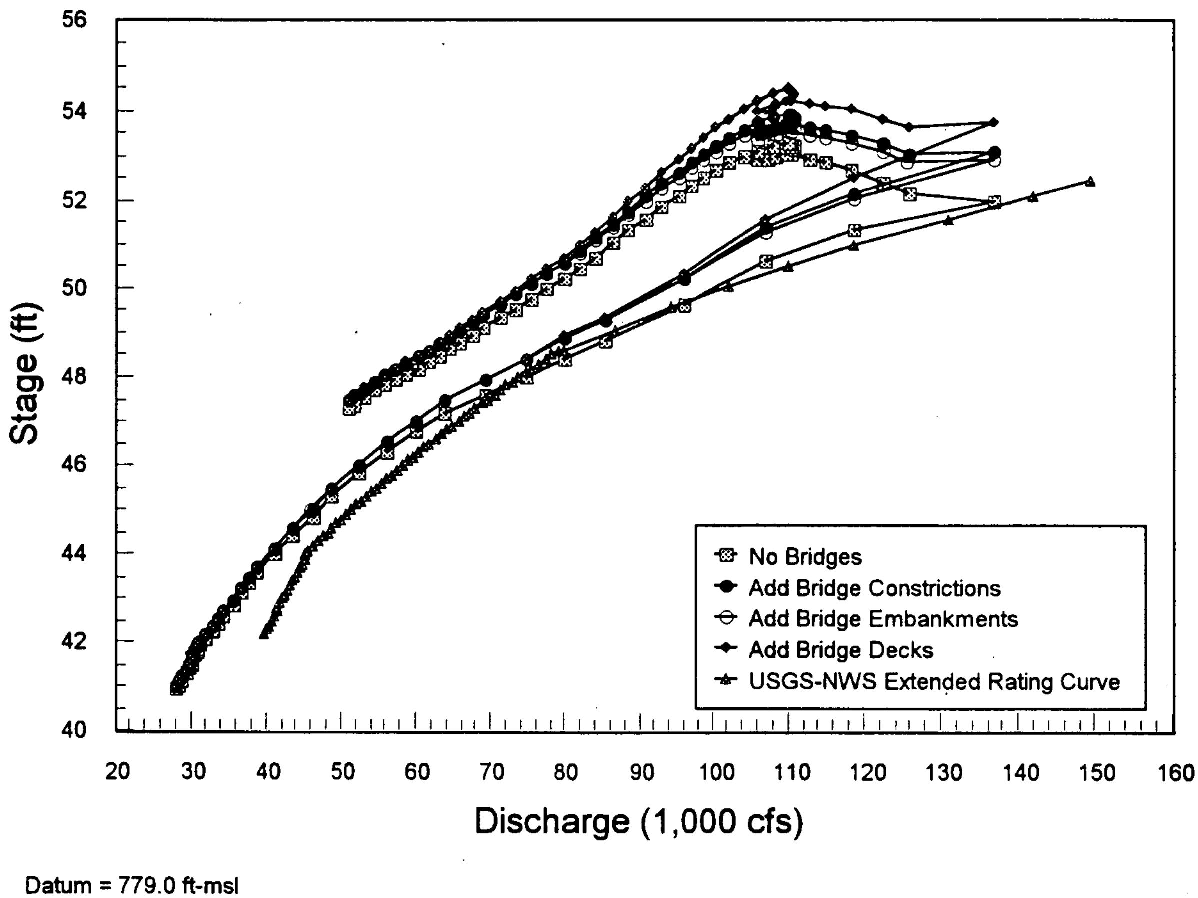

Figure B-14. Rating Curves at East Grand Forks, MN (Effects of Bridge Components).

the Bygland Coulee and 11,000 cfs in the secondary coulee. The peak flow determined by the USGS at the East Grand Forks gage (mi 297.65, 0.35 miles below the Red River of the North-Red

Lake River confluence) was 137,000 cfs. The outbreak of flow from the Red River of the North into the coulees was thought by some to have produced additional flow (27,000 cfs) at the gage. As stated previously, the NWS forecast a peak flow at the gage of 110,000 cfs which is the sum of the inflows from the Red River of the North (80,000 cfs) and the Red Lake River (30,000 cfs).

To determine the effect of the coulees on the flow at the East Grand Forks gage, the Red-coulee-Red Lake river system was modeled using FLDWAV. As shown in Figure B-5, the river system consists of the Red River of the North from the Thompson Road Bridge (mi 317.68 - 0.5 mile upstream of where the outbreak occurred) to just below the Red River of the North-Red Lake River confluence (mi 298.0), the Red Lake River from mi 16.2 to its confluence with the Red River of the North, the 12-mile reach of the Bygland Coulee, and the 7.4-mile reach of the secondary coulee. The inflow hydrographs on the Red River of the North at Halstad (about 58 miles above the upstream boundary) and on the Red Lake River at Crookston (about 34 miles above the upstream boundary) were used as upstream boundary conditions. The stage hydrograph generated by FLDWAV at the upstream end of the reach (mi 298.0) in the previous study was

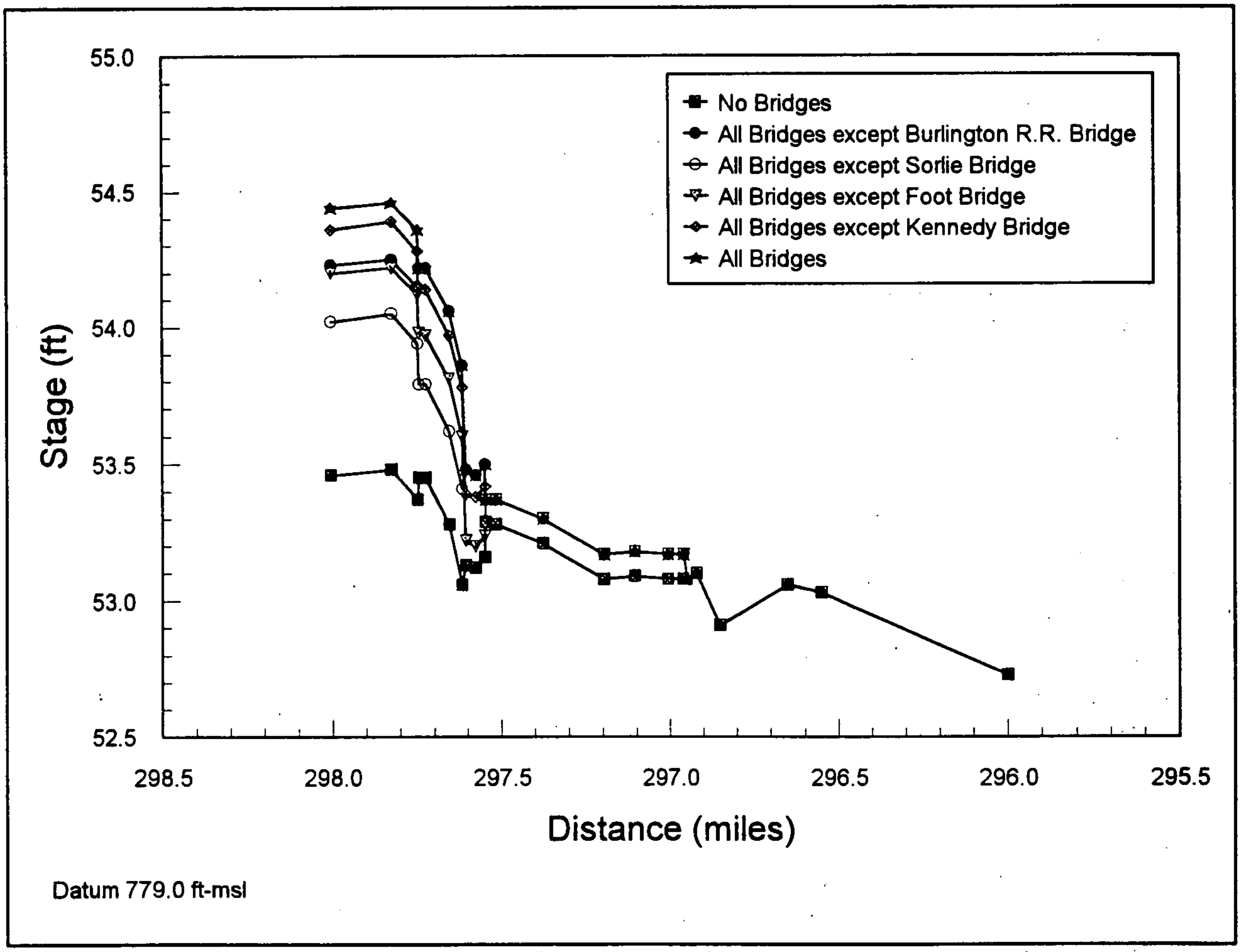

Figure B-15. Peak Stage Profiles Showing Effects of Bridges.

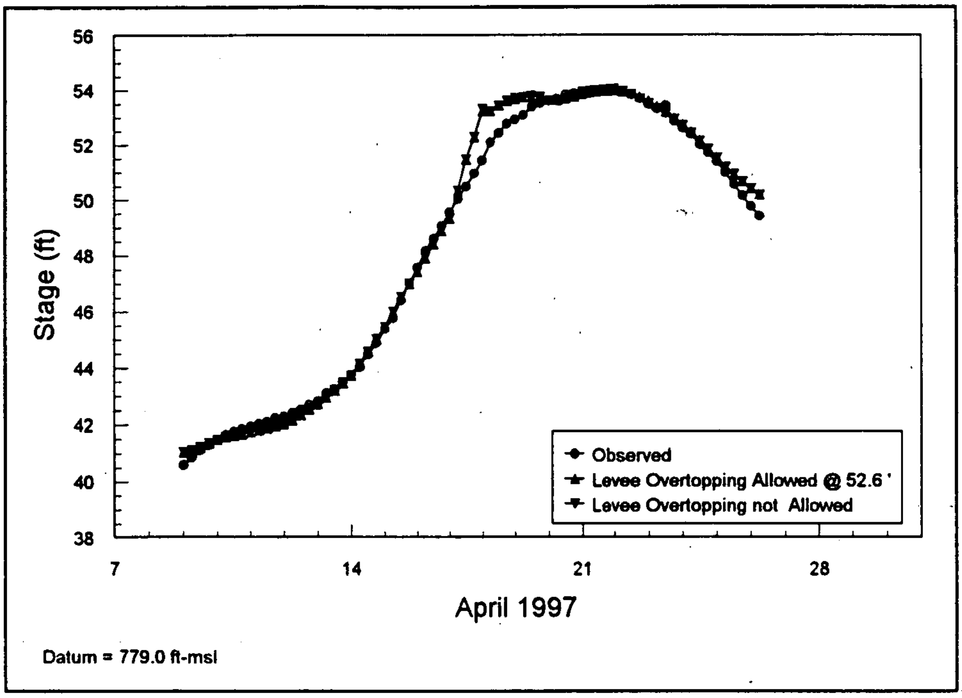

Figure B-16. Stage Hydrographs at East Grand Forks, MN (Levee Effects).

used as the downstream boundary condition in the current study. The outbreak on the Red River of the North was modeled as a weir with a maximum peak outflow of ~30,000 cfs (which was reasonably close to 27,000 cfs in question) being released from the Red River of the North and entering the Bygland Coulee near its upstream end (mi 12.00). A portion of the flow entering the Bygland Coulee was diverted into the secondary coulee. This diversion was modeled as a weir with a maximum peak outflow of ~10,000 cfs entering the secondary coulee near its upstream end (mi 7.40). Although FLDWAV generated peak discharges of 30,000 cfs within the Bygland Coulee and 10,000 cfs within the secondary coulee, the peak flow at the downstream end (mi 298.0) of the river system remained ~110,000 cfs. Thus, the 30,000 cfs peak flow that left the Red River of the North and proceeded down the two coulees resulted in a decrease of the Red River of the North flow from 80,000 cfs to 50,000 cfs. This 50,000 cfs then combined with the 30,000 cfs from the two coulees along with the 30,000 cfs in the Red Lake River to produce a total flow of 110,000 cfs below the confluence. Therefore, no additional flow resulted below the confluence due to the coulee effect.

To account for additional storage above the coulee which may have contributed to the flow after the outbreak, the upstream boundary on the Red River of the North was extended ~50 miles upstream of the Thompson Road Bridge. Although the peak flow into the Bygland Coulee increased due to the availability of water which had been in storage on the Red River of the North, the peak flow on the Red River of the North was attenuated as it moved through the 50-mile storage reach. Therefore, the peak flow below the Red River of the North-Red Lake River confluence did not increase beyond the inflow amounts.

In summary, the flows through the coulees do not appear to have increased the discharge below the confluence of the Red River of the North and the Red Lake River by either adding to the ability of the combined system to convey inflows in the Red River of the North downstream to the confluence or by draining waters stored in the Red River of the North. For the coulee flows to have had an impact, some source of water not included in the inflow hydrographs from Halstad, Minnesota, and Crookston, Minnesota, would be required.

Conclusion

Table B-3 lists a summary of the conditions that were not captured with the single-valued rating curve used by the NWS for the April 16 forecast of ~50.5 ft at 110,000 cfs at the East Grand Forks gage (mi 297.65) on the Red River of the North. The primary hydraulic condition contributing to the increase in stage between the observed crest (54.35 feet) and the crest produced by the single-value rating curve of 50.5 feet was a +2.0 foot backwater effect (hysteresis loop rating phenomenon) due to a rapidly rising hydrograph flowing through a river with a very mild slope and a backwater effect of +0.8 foot due to the four bridges wherein the primary contributor was the Sorlie Bridge (+0.4 foot). The effect of not including the first peak in the modeled discharge hydrograph also contributed to +0.4 foot to the error in the NWS forecast. The failure of the levees was found to have had a minimal effect of lowering the actual stage by 0.04 foot.

Table B-3. Contributing Factors to the Peak Stage Simulation Error at the East Grand Forks Gage (mi 297.65).

Unsteady backwater (loop-hysteresis) effect (Combined bridge/backwater (2.8 feet) - bridge (0.8 feet))	+2.0 feet
Bridge Effects	+0.8 feet
Effect of First Discharge Peak	+0.4 feet
Levee Effects	-0.0 feet
Unexplained	+0.6 feet
Total Effects	**+3.8 feet**

APPENDIX C

Survey Team Members and Itinerary

Survey team members serve on the basis of their personal expertise; i.e., they are not asked to represent the official position of their respective agencies. This report was compiled by a survey team composed of the following ten members:

Co-Leaders of the team:

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Meteorologist in Charge
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(9) Jim D. Versteeg
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Survey Itinerary

The field portion of the survey was conducted by nine of the ten members of the team over the four-day period May 27-30, 1997. Damages to the area around Grand Forks were so extensive that it was necessary to delay the start of the survey until hotel accommodations could be provided following restoration of water, power, and other infrastructure. Janice Lewis, who is the primary author of the hydraulic analysis, did not participate in the field portion of the survey. The survey team had an initial organizational meeting on Monday evening, May 26, and spent Tuesday, May 27, at the North Central River Forecast Center (NCRFC) in Chanhassen, Minnesota, and at the collocated National Operational Hydrologic Remote Sensing Center (NOHRSC). On

Wednesday, May 28, two team members (Hartman and Page) continued meetings with the NCRFC and NOHRSC, while other team members met with the Minnesota Department of Emergency Management in St. Paul, the FEMA Disaster Field Office in St. Paul, and the St. Paul District Office of the U. S. Army Corps of Engineers. The team made an evening flight to Grand Forks, North Dakota, on Wednesday, May 28. On Thursday, May 29, the team was interviewed by local media at the Eastern North Dakota National Weather Service Office (call sign FGF) in Grand Forks, North Dakota. Meetings with the staff of the FGF office continued on Thursday afternoon as the team broke up into smaller groups to meet with a number of local officials. On Friday, May 30, three team members (Bryant, Jensen, and Yorke) flew to Bismarck to meet with the Bismarck NWS Forecast Office, the U.S. Geological Survey, the FEMA Disaster Field Office in Bismarck, and state of North Dakota officials including the North Dakota Water Commission and the Department of Emergency Management. Meanwhile, other team members continued meetings with local officials. Professor Leon Osborne of the University of North Dakota was also interviewed on Friday. One team member (Johnson) drove to Fargo to meet with Lou Bennet of the spin-down NWS office, with Dennis Walaker of the City of Fargo, and with Terry Lejcher of the Minnesota Department of Natural Resources. The entire team reconvened on the evening of Friday, May 30, to review initial findings and recommendations and to discuss writing assignments for the draft service assessment.

Survey Contacts

A partial list of survey team contacts follows:

North Central River Forecast Center (NCRFC)
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Jim Campbell, Grand Forks County, AND
Dick Turner, Minnesota Emergency Management

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- Dave Schaffer, St. Paul Pioneer Press, 6/23/97
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- Jim Shaw, WDAY-TV, Fargo, 5/30/97
- Kevin Dean, KCNN Radio, Grand Forks, 6/4/97
- Gerry Gilmour, The Forum, Fargo, 6/4/97

Special thanks to:
- Lt. Steven Pape
- Lt. Barry Choy
- Pilots/Airborne Snow Survey Program