PART SIX

FORECASTING AND PRECIPITATION RECORDS

CHOOSING A HYDROLOGIC MODEL FOR FLOOD FORECASTING

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Introduction

The most common application programs in automated flood warning systems are the runoff and river forecast programs. These programs use observed and, in some cases, forecast rainfall amounts to compute the amount of water that will enter the stream system.

Forecast Models

The purpose of a forecast model is to estimate future river flows and elevations based on observed or forecast amounts of rainfall. In flash flood situations, certain portions of the forecast hydrograph are more important than others. Accurate forecasts of the rising limb, the time to hydrograph peak, and the magnitude of the peak are critical. These are the elements of model output that have the most impact on the flood warning. The model implemented in a flood warning system must consistently perform well in these three areas.

Before model selection, one very important element, rainfall estimation, must be considered. The volume of water under the rising limb of a flash flood hydrograph is primarily surface runoff. Basins with short response times are often characterized by low infiltration rates and steep slopes which efficiently generate runoff. Because these basins efficiently generate runoff, especially during periods of high intensity rainfall, the volume of runoff is very sensitive to the volume of rainfall. This implies that the output of a flash flood forecast model will also be very sensitive to the rainfall inputs.

Flash flood forecast sensitivity to rainfall inputs serves to emphasize the importance of establishing a good measurement system first. The phrase commonly heard in the computer industry, "Garbage in, garbage out," is equally applicable to flash flood forecasting. Good model performance, no matter what model is used, cannot be expected without a good measurement system. The implication for forecast system design is to invest in the measurement and detection systems first, then consider hydrologic models.

There are many different hydrologic forecast models in use. The most commonly used models in local flood warning systems fall into two categories: simple index-type models, and conceptual rainfall-runoff models. Index models keep a running index that reflects current moisture conditions. The moisture index, a "time of year" index, current rainfall, and rainfall duration are generally all that is needed to estimate surface runoff with these models. Conceptual models attempt to provide a more "physically-based" approach to basin modeling by more explicitly accounting for evapotranspiration, interception storage, retention storage, infiltration, surface runoff, percolation, interflow, etc. Table 1 shows the most widely available models for local flood warning systems.

Table 1. Flood forecast models.

Index Models	Conceptual Models
API	Sacramento Soil Moisture
ADVIS	HEC1-F
Flood Advisory Tables	SSARR

API Model

The API (Antecedent Precipitation Index) model was developed by the National Weather Service (NWS) and has been used in various forms since the 1950s. The antecedent precipitation index reflects the current soil moisture based on recent rainfall. A high index means high soil moisture content while a low index indicates dry conditions. The API for a given period is used with a rainfall-runoff relationship, the rainfall amount, and the storm duration to estimate runoff. A unit hydrograph is applied to distribute the runoff. At each computational period, the index is updated based on the additional rainfall and by a seasonally dependent factor. The seasonally dependent factor empirically accounts for changes in the rainfall-runoff relationship due to seasonal changes in evapotranspiration, infiltration, etc.

Complex basins can be modeled by applying the API technique to individual sub-basins that are hydrologically homogeneous. Outflows from sub-basins can be routed downstream and combined with other tributary flows and inflows calculated by the API model for local areas.

Many versions of the API model exist. Most NWS River Forecast Centers that use API have added modifications to "customize" the technique for conditions in basins within their area of responsibility. At least eight different implementations of API are used by the NWS.

The API model is simple and relatively easy to understand. It is also relatively easy to adjust. Forecasters can easily change model parameters or model runoff based on their assessment of the current event to improve model performance.

ADVIS

The ADVIS program (Sweeny, 1988), developed by the NWS for local flood warning, includes an API model as its primary hydrologic forecast technique. (All NWS implementations of API are available in ADVIS.) ADVIS is a simplified implementation of hydrologic modeling that produces output appropriate for the user depending upon what type of information is available. For example, ADVIS output includes:

- Categorical forecasts for ungaged watersheds. Categorical forecasts are general forecasts of "minor," "moderate," or "severe" flooding based on the antecedent precipitation index and rainfall estimates.
- Crest stage forecast. ADVIS will generate a crest forecast if the unit hydrograph peak is available.
- Forecast hydrograph. Where the complete unit hydrograph is available, ADVIS generates a complete forecast hydrograph.

The ADVIS program is intended to address relatively simple hydrologic situations at the local level.

Flood Advisory Tables

Flood advisory tables are used to provide a quick estimate of peak stage forecasts using indices produced by the API or other modelling techniques. The tables are computed in advance for a variety of antecedent conditions. The current index can be computed on-site or provided by a local NWS office. Local users apply the current index with the latest rainfall estimate to the table to determine the estimated peak stage. An estimated time to peak is usually available based on previous analysis of basin response.

Sacramento Soil Moisture Accounting Model

The Sacramento Soil Moisture Accounting Model is a conceptual model designed as a comprehensive representation of the hydrologic processes of the upper soil mantle. Evapotranspiration, direct runoff from impervious areas, surface runoff, percolation, interflow, and two types of base flow are explicitly represented. Runoff calculated for each period is distributed using a unit hydrograph.

Each hydrologic process is represented by a function or series of functions with adjustable parameters. The model is calibrated with historical rainfall and streamflow data by adjusting parameters until the model output adequately represents basin response. The model is applied to individual basins that are hydrologically homogeneous. Complex basins are modeled by combining outflows from individual basins using a variety of available routing techniques.

HEC1-F

The Hydrologic Engineering Center (HEC) has developed a forecasting system for Corps of Engineers offices that is also available for local flood warning systems. The forecast technique uses an initial and uniform loss rate to compute runoff, which is applied to a unit hydrograph to produce a basin forecast. Results from each basin can be combined and routed to develop forecasts for complex systems. HEC 1-F uses observed streamflows to set proper loss rate parameters.

HEC1-F can be calibrated relatively easily. Most of the necessary parameters can be obtained from maps. Infiltration parameters and certain characteristics of the unit hydrograph can be estimated initially. During a flood, HEC1-F evaluates model performance against observed stream flow and automatically adjusts the appropriate parameters.

HEC1-F is the forecast version of HEC1, a widely used hydrologic design tool. Many different public and private organizations throughout the United States have used HEC1 to generate flood hydrographs for a variety of purposes from bridge design to floodplain mapping. As a result, many local engineers understand the model and the transition to HEC1-F is relatively easy.

SSARR

The Synthesized Streamflow and Reservoir Regulation (SSARR) model was developed jointly by the NWS and the Corps. It is a tool used by the respective agencies in the Pacific Northwest for flood forecasting and reservoir regulation. The SSARR model provides a continuous accounting of soil moisture to determine how much of the incident rainfall and snowmelt will become runoff. Three phases of runoff are computed: direct runoff, interflow, and baseflow. Each phase is routed through a series or cascade of linear reservoirs to produce the total streamflow.

Hydrologic Model Selection

Choosing the "appropriate" hydrologic model is a task open to much debate. A widely cited study by the World Meteorological Organization indicated that the API technique, the Sacramento model, and the SSARR model all gave about the same results in humid climates. However, explicit soil moisture accounting models like SSARR and the Sacramento model were clearly superior to the API model for arid and semi-arid climates. In humid environments, soil moisture conditions are less variable than in arid or semi-arid climates. The added complexity of the explicit soil moisture accounting models to handle wide-ranging conditions does not contribute significantly to model performance when conditions are relatively stable. However, when conditions are rapidly changing, some researchers have found that explicit soil moisture accounting models offer a significant performance advantage.

When reviewing studies comparing the complex explicit soil moisture accounting models with simpler index approaches, an important insight was noted. While the simpler models performed well statistically compared to the explicit soil moisture accounting models, significant deviations occurred at key points. These deviations, while significant, were rare and tended to have little effect on the overall statistics. However, the deviations were frequently observed when extreme hydrologic conditions existed. The complex models could manage the extremes where the simpler approaches were not capable of doing so. These rare events are precisely the events that offer the greatest potential for hazard mitigation.

The choice of models in specific situations remains difficult. After all the analysis of which model performs the best for a given basin, it ultimately depends upon the capabilities and resources of local users. Complex models requiring a high level of support might be appropriate in cases where local skills and resources can handle it. However, the same model may be entirely inappropriate in situations with lower levels of local hydrologic skill and resources.

To summarize model selection:

- Choose a model that is within the capabilities of the local user to understand, operate, and maintain;
- Choose a model that is appropriate for the local hydrologic regime; and
- Choose a model that will provide the best estimate of the rising limb, the time to peak, and the flood peak.

References

Burnash, Robert J. C., R. L. Ferral, and Richard L. McGuire
1973 *A Generalized Streamflow Simulation System*. Sacramento, Calif.: National Weather Service, California Department of Water Resources.

Dotson, Harry W. and John C. Peters
1990 "Hydrologic Aspects of Flood Warning—Preparedness Programs." Technical Paper No. 131. Davis, Calif.: U.S. Army Corps of Engineers Hydrologic Engineering Center.

Federal Interagency Advisory Committee
1985 *Guidelines on Community Local Flood Warning and Response Systems.* Springfield, Va.: National Technical Information Service.

Kitanidis, P. R., and R. L. Bras
1980 "Real-Time Forecasting with a Conceptual Hydrologic Model, 2: Application and Results," *Water Resources Research* 16(6): 1034–44.

Linsley, Ray K., Max Kohler, and Joseph L. H. Paulhus
1982 *Hydrology for Engineers.* Third Edition. New York: McGraw-Hill.

Nemec, J.
1984 "Design and Operation of Forecasting Operational Real-Time Hydrological Systems (FORTH)." Unpublished manuscript, Figure 12. Geneva, Switzerland: World Meteorological Organization.

Pabst, Art
1986 "State-of-the-Art Flood Forecasting Technology." *Proceedings of a Seminar on Local Flood Warning—Response Systems.* U.S. Army Corps of Engineers.

Sittner, Waiter T.
1985 "Catchment Response in the Computer Age." Pp. 749–57 in Harry C. Toro, ed., *Computer Applications in Water Resources.* New York: American Society of Civil Engineers.

Sittner, W. T., C. E. Schauss, and John Monroe
1969 "Continuous Hydrograph Synthesis with an API-Type Hydrograph Model." *Water Resources Research* 5(5): 1007-22.

Sorooshian, Soroosh
1988 "Identifiability in Conceptual Rainfall-Runoff Models." Pp. 172-83 in *Computerized Decision Support Systems for Water Managers.* Proceedings of the 3rd Water Resources Operations Management Workshop. New York: American Society of Civil Engineers.

Sweeny, Timothy L.
1988 "Flash Flood Hydrologic Forecast Model, ADVIS." Pp. 683-92 in *Computerized Decision Support Systems for Water Managers.* Proceedings of the 3rd Water Resources Operations Management Workshop. New York: American Society of Civil Engineers.

U.S. Army Corps of Engineers
1988 "General Guidelines for Comprehensive Flood Warning/Preparedness Studies." Davis, Calif.: Hydrologic Engineering Center.

U.S. Army Corps of Engineers Hydrologic Engineering Center
1988 "Floodway Determination Using Computer Program HEC-2." Training Document No. 5.

U.S. Army Corps of Engineers
1989 "Water Control Software: Forecast and Operations." Davis, Calif.: Hydrologic Engineering Center.

U.S. Army Corps of Engineers
1991 *SSARR User's Manual.* Portland, Ore.: U.S. Army Corps of Engineers, North Pacific Division.

World Meteorological Organization
1975 *Intercomparison of Conceptual Models Used in Operational Hydrologic Forecasting.* Operational Hydrology Report No.7. Annex III. Geneva, Switzerland: WMO.

REAL TIME FLOOD FORECASTING: STILLWATER, OKLAHOMA

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Introduction

After the passage of a particularly severe flood it is not uncommon for the agency responsible for issuing flood warnings and/or operating flood control systems to come under public criticism for the manner in which it carried out its function. In the case of the operation of a flood control reservoir, downstream property owners may complain that the gates to the structure were not opened at the optimal time, thus subjecting them to flooding that should have been prevented by the flood control reservoir. Property owners around the reservoir may complain that the gates were opened too late and caused excess damage to their property. In other instances citizens may not be warned early enough for effective measures to be taken to protect property, or evacuations may be ordered without a flood occurring. Agencies generally operate the flood control systems as well as possible with the information available about the rainstorm and flows producing the problem. Effective operation of flood warning and flood control systems requires accurate information on past, current, and projected flow and rainfall so that good estimates of expected flood flows can be made.

Two important aspects of a flood warning system are lead time and accuracy. These aspects are interrelated in that as the required lead time gets shorter, the accuracy of the projection improves until at a lead time of zero a perfect "projection" can be made. What is required is a long lead time with high accuracy.

The approach to addressing the lead time/accuracy problem will depend on the size of the watershed producing the flood flows. On small basins, flow estimates for long lead times are heavily dependent on the expected rainfall pattern. For larger basins the flow that will occur over the next few hours is already in storage and transit within the watershed so the accuracy of the flow projection depends on the determination of the quantities of water in the system and the routing of this water to the point of interest. For intermediate-sized watersheds, rainfall forecasts, estimation of abstractions from rainfall, and flow routing all play a role in determining the accuracy of the flood forecast.

Objectives

This project was undertaken to improve the flood forecasting and flood warning capabilities of the Civil Defense Office in Stillwater, Oklahoma. The objectives of the project being reported on here are:

- Develop a real-time parameter optimization scheme for a rainfall-runoff model.
- Develop an algorithm for forecasting rainfall on a grid-cell basis based on storm movement, intensity, areal extent, and orientation.
- Develop a continuously updated flood flow prediction scheme using optimized parameters, observed rainfall, and forecasted rainfall.

Procedure

A network of nine rain gages and seven water level recorders has been installed in the 276.9 square mile drainage basin contributing flow through Stillwater. Data from these gages are telemetered into the Civil Defense Office where they can be combined with WSRD-88 radar rainfall estimates and used in a hydrologic modeling framework to project flows that are likely to occur within Stillwater over the next several hours. The hydrologic model being used is the SCS TR-20 hydrology model. Model control has been modified to allow for real time calibration of the curve number parameters which are used to estimated runoff volume from rainfall. The total basin has been divided into seven subbasins requiring seven curve numbers to be estimated.

The model and data collection program are synchronized so that every 10 minutes or so new information on rainfall and water levels in streams and reservoirs is used by the model to optimize the value of the estimated curve number. The sequential steps for each time increment are:

1. Input data on current rainfall and water levels.

2. Optimize the estimated curve number for each subwatershed based on the measured rainfall, measured water levels, and the predicted water levels. This optimization is based on a minimization of the sum of squares of the prediction errors involving water levels.

3. Based on current rate of storm movement, estimate the rainfall that is likely to occur over the next two hours.

4. Based on current rainfall, projected rainfall, and the optimized curve numbers, project ahead in time the estimated flow.

5. These steps are repeated every 10 minutes or so as the storm moves across the drainage area.

The advantage of this procedure is that it enables one to use quite complex models with the assurance that the predictions being made by the model are reasonably accurate since at the end of each time step, the model parameters are reoptimized based on the observed data that are being telemetered to the central office and input to the modeling system.

As the radar data becomes more readily available, it will be used to more precisely define the spatial pattern of the rainfall. The actual gages will provide data that will be used to continually calibrate the radar to the ground "truth" in the form of the measured data. Radar patterns will also be used to project several time steps ahead so that an estimate of the amount of rain that will occur over the next hour or so will be made. This rainfall estimate is combined with observed rainfall amounts and used in the hydrologic model to predict flood flows. Since the hydrologic model is calibrated every 10 minutes, error in the estimated hydrographs is limited and is corrected based on the measured data.

Output from the model is displayed graphically as hydrographs at various locations in the basin. The model control and optimization algorithms are programmed in C and TR-20 is written in FORTRAN. An Intel 80486-based microcomputer running at 30 mHz or faster is sufficient to keep up with a storm in real time. The procedure used to address each specific objective follows.

Objective 1

This implementation is on intermediate-size basins (276.9 square miles) where all four of the major components of an effective rainfall-runoff modeling system for flood forecasting are considered:

- Estimation of the temporal and spatial distribution of rainfall;

- Transformation of rainfall into rainfall excess;

- Routing rainfall excess to the channel system; and
- Routing flow through the channel system.

Rain gage and radar data will be used to define the rainfall input. TR-20 will be used to convert rainfall into an estimate of streamflow. Initial hydrologic model parameter estimates are based on past experience in the watershed. These estimates will be updated as the storm and runoff event of interest develops in time through a self-calibration procedure programmed into the model. The objective function is a minimization of a sum of squares of deviations between predicted and observed flows weighted to give the most recent observations more importance than earlier flows. Parameter estimates are updated after each time step as the storm develops and additional flow data become available. At the conclusion of the storm, the historical data base will be updated. These updated parameters will then serve in the model for the next storm simulation.

Objective 2

There are several characteristics of rainfall that affect runoff. Of major importance are the temporal pattern, spatial distribution, and storm movement. Generally for small watersheds, the peak rainfall intensity is the most important characteristic in determining peak runoff rate. The spatial distribution is needed to account for the variation in rainfall depth within the watershed, and it helps predict runoff for moderate to large watersheds.

Parameters of interest are those that characterize the velocity vector of the storm and the size and orientation of isohyets. The forecasting of these parameters will be used to superimpose a moving storm over a grid of points defining the watershed and then used to simulate the runoff response. Storm parameters will be updated as additional information is obtained from radar.

Objective 3

Using the optimized model parameters, observed rainfall, and forecasted rainfall, flow forecasts will be made with the hydrologic model. The entire process of parameter optimization, rainfall forecasting, and flow forecasting will be repeated approximately every 10 minutes in real time as updated information on the development of the rainstorm becomes available from the radar system and observed streamflow data become available from a telemetric stream gaging station. In this way, the flow forecast will be dynamic and improving as any particular forecast time is approached.

Figure 1 shows a sequence of three dimensional plots of rainfall in the Stillwater area for a storm on March 30, 1993. The individual plots are 6 minutes apart. From this figure the progression of the storm across the area is

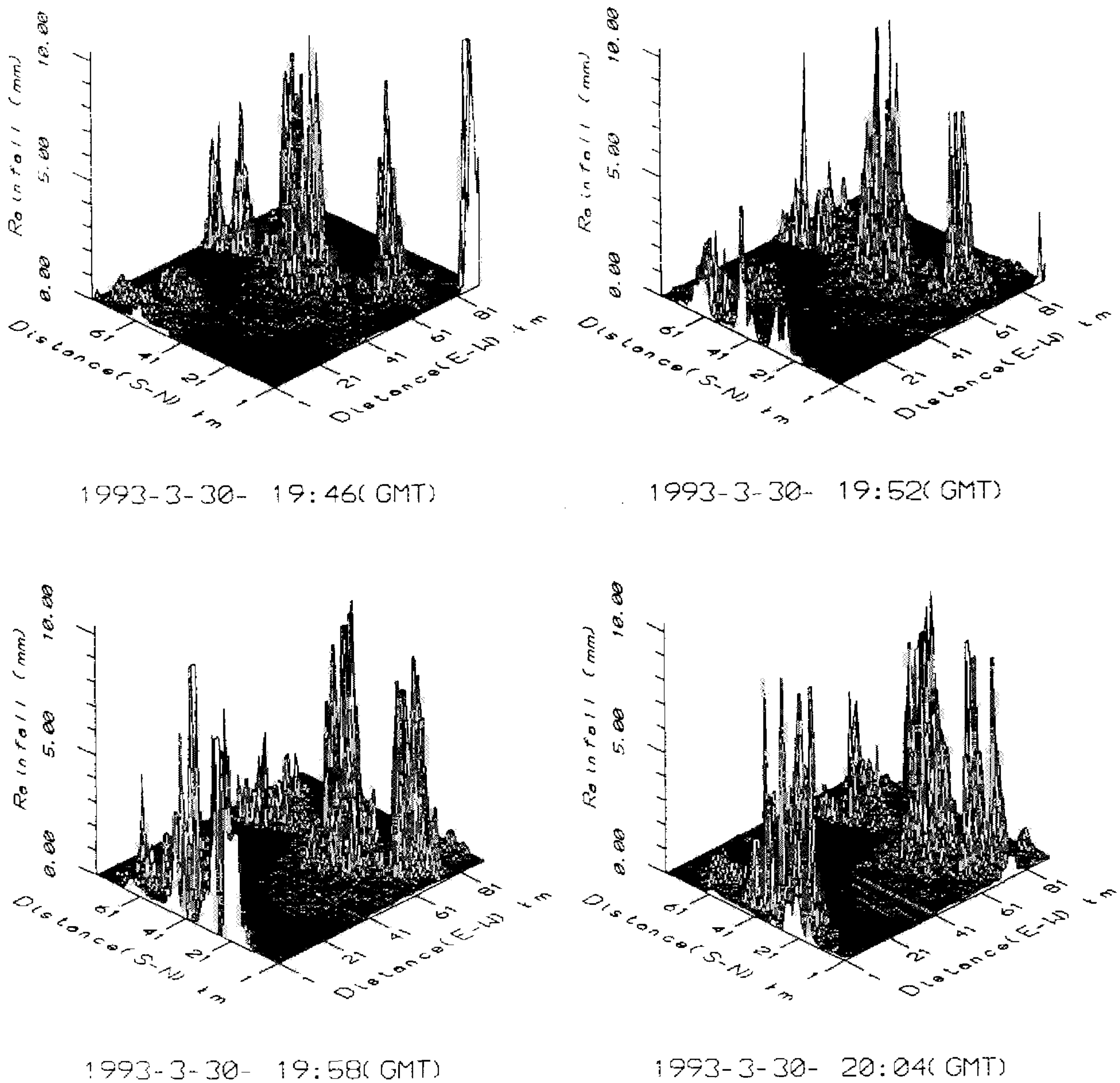

Figure 1. *The sequence of three dimensional plots of rainfall in the Stillwater area.*

readily apparent. This is the type of data that will be used as input to the hydrologic model.

Figure 2 shows hydrographs for seven locations in the basin at a particular time. The hydrographs contain the actual or measured data up to the current time and the estimated flow to the current time and the projected flow for several time steps in the future. It is the ability to anticipate rain and the resulting runoff coupled with continuous calibration of the hydrologic model that makes this approach valuable.

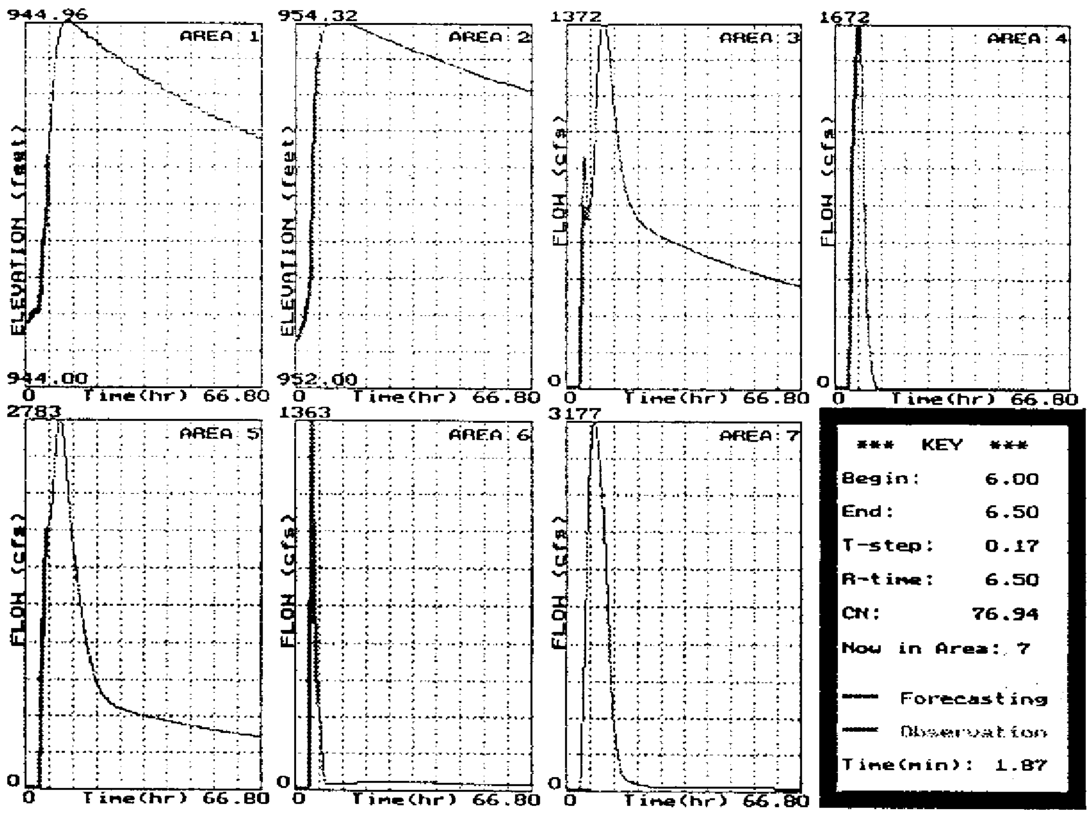

Figure 2. Hydrographs for seven locations in the basin at a particular time on the screen.

USE OF WSR-88D AND SURFACE RAIN GAGE NETWORK DATA IN ISSUING FLASH FLOOD WARNINGS AND MAIN STEM FLOOD FORECASTS

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Introduction

On the morning of June 5, 1991, a series of thunderstorms produced excessive rainfall over Osage County, Oklahoma, ending at approximately 7:00 a.m. This rainfall produced a flash flood over the headwaters of the Bird Creek drainage basin. The runoff ultimately produced a rise on Bird Creek, at Avant, Oklahoma, from 3.3 feet at 7:00 a.m. to the flood stage of 16 feet in less than 12 hours. Bird Creek crested at Avant 24 hours after the rainfall event, at a stage of 22.88 feet, or 6.88 feet above flood stage.

Timely flash flood warnings were issued for the event, although river gage reports at 7:00 a.m. indicated no rise on the stream. Therefore, only rainfall estimates could be used to forecast the eventual flood at Avant, which is the first river gage below the headwaters. Rainfall estimates across Osage County and surrounding areas indicated a maximum amount of 4.00 inches. However, the Weather Surveillance Radar 1988 Doppler (WSR-88D) estimated a maximum of 9.1 inches, and indicated the heaviest rainfall occurred over an area void of surface rain gage stations. In addition, the thunderstorms produced hail, which is known to result in overestimates of rainfall by the WSR-88D (Ahnert et al., 1983).

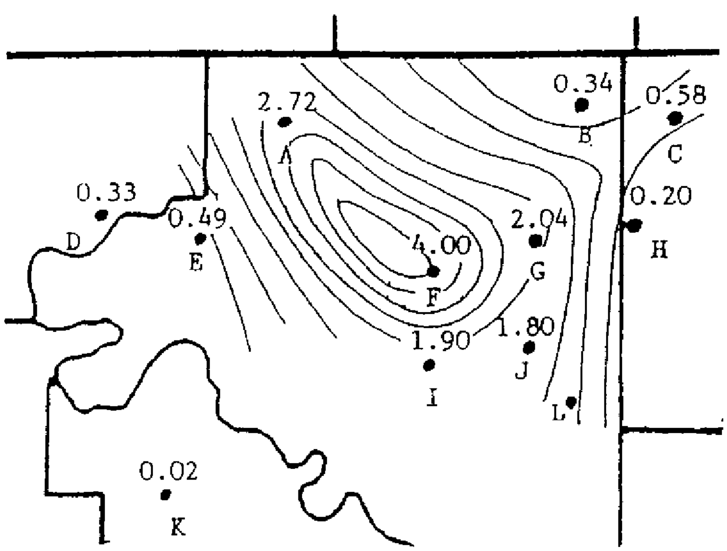
Forecasters from the Tulsa Weather Service Office (Tulsa WSO) and the Tulsa River Forecast Center (Tulsa RFC) made estimates of basin average rainfall by subjectively combining the radar data and surface reports. These subjective adjustments were quite good and allowed headwater forecast models to predict the flood that occurred at Avant. After the fact, a simple objective analysis was used to combine the two data sources, which also produced a reasonably accurate flood forecast along Bird Creek. Both methods validate that the combination of radar and rain gage data can be used in real-time to make accurate and timely warnings and forecasts.

Chronology

Beginning around 3:00 a.m., June 5, 1991, a series of thunderstorms developed over Osage County, Oklahoma. The convection developed over the headwaters of the Bird Creek drainage basin and moved slowly east, nearly parallel to the basin. During the next three hours, convection redeveloped two more times over the same area.

There were several reports of moderate-sized hail (0.75 to 0.88 inch) during the event. Severe thunderstorm warnings were issued almost continuously during that same time for Osage County and surrounding areas. By 5:00 a.m., the WSR-88D indicated over 5 inches of rainfall had occurred over portions of Osage County, and a flash flood warning was issued. Between 6:00 a.m. and 7:00 a.m., the thunderstorms began moving rapidly southeast away from the basin. Property damage in Osage County was minimal due to the rural setting, though a comparable event over a metropolitan area would have likely resulted in substantial damage.

By 7:00 a.m., the WSR-88D estimated a 9.1-inch storm precipitation maximum just west of Pawhuska. Rainfall estimates from law enforcement agencies, civil defense offices, and the general public were between five and seven inches for storm totals west of Pawhuska. However, official rainfall reports from cooperative observers (Figure 1) were well below the radar estimates, with a maximum of 4.00 inches at Pawhuska. Flash flooding was finally reported just west of Pawhuska around 8:15 a.m., with water 3 to 4 feet deep over highway 60 west of town.



Site	Observed report (inches)	WSR-88D estimate (inches)
A	2.72	4.0-5.0
B	0.34	1.0
C	0.58	1.0
D	0.33	1.0-2.0
E	0.49	2.0-3.0
F	4.00	7.0-8.0
G	2.04	4.0-5.0
H	0.20	1.0-2.0
I	1.90	4.0-5.0
J	1.80	4.0-5.0
K	0.02	1.0

F - Pawhuska, OK
L - Avant, OK

Figure 1. *Isohyetal analysis of rain gage reports, and table of reports corresponding to WSR-88D estimates.*

It was apparent that main stem flooding was imminent. At that time, forecasters in the WSO made subjective estimates of basin average rainfall; all sources were used and biases were considered. The estimate of basin average rainfall was then used in a local program to estimate a 12-hour river rise at Avant, the first river gage below the Bird Creek headwaters. The program calculated a rise to 19.5 feet by 7 p.m. on June 5. Flood stage at Avant was 16 feet. A Flash Flood Statement was then issued to alert persons along Bird Creek that main stem flooding was likely from Pawhuska to Avant during the afternoon.

The Tulsa RFC also made another estimate of basin average rainfall by using all sources, including WSR-88D, rain gage data, satellite estimates, and unofficial reports. That estimate was used in conjunction with the Sacramento Soil Moisture Accounting Model (Burnash et al., 1973) to determine forecast stages for river gage locations along Bird Creek. At 2:25 p.m., the RFC forecast the stage at Avant to reach 19 to 20 feet (3 to 4 feet over flood stage) by midnight. At that time, a Flood Warning for Bird Creek was issued. At 7:00 p.m., the stage at Avant had already reached 19.5 feet. The RFC issued a revised forecast at 9:25 p.m. for a crest of 22 to 23 feet in the early morning of June 6. The maximum recorded flood crest was 22.88 feet on June 6, at 3:00 a.m., followed by a rapid decline late that day.

Correctly estimating the basin average rainfall, for use in flood and flash flood forecasting, was critical. The maximum rain gage report was 4.00 inches while radar data indicated over 9.00 inches. Although rain gage data provided the most accurate point measurements of rainfall, the WSR-88D provided much better geographical, or spatial, representation of the event. This gave forecasters important information in deciding where and how much rainfall occurred.

Independent Data Analysis

The storm precipitation totals for Osage County were quite varied, as indicated from the surface rain gage reporting network (Figure 1). When data from the WSR-88D was included, it became obvious the reporting network was not sufficient to resolve the event. Surface rain gage data indicated a storm total maximum of only 4.00 inches. Other reports around the area indicated even less rainfall. An objective analysis of these rain gage reports alone indicated a basin average rainfall of only 1.44 inches above Avant. This analysis resulted in a forecast crest of 12 feet, 4 feet below the flood stage of 16 feet (Figure 2). However, analysis of WSR-88D data indicated a basin average storm total of 5.2 inches. Using the radar data alone resulted in a 12-hour stage forecast of 32 feet, the highest stage ever recorded at Avant. This forecast was obviously too high, considering that the WSR-88D estimated almost 3 inches too much rain at Pawhuska. Clearly, a compromise between the two data sets was required.

Objective Methods of Combining Data

The subjective analysis of combining radar and rain gage data worked well enough to forecast the resulting flood on Bird Creek at Avant. However, an objective analysis of the data also arrives at a good estimate of basin average rrainfall, and therefore a reasonable forecast of the flood at Avant.

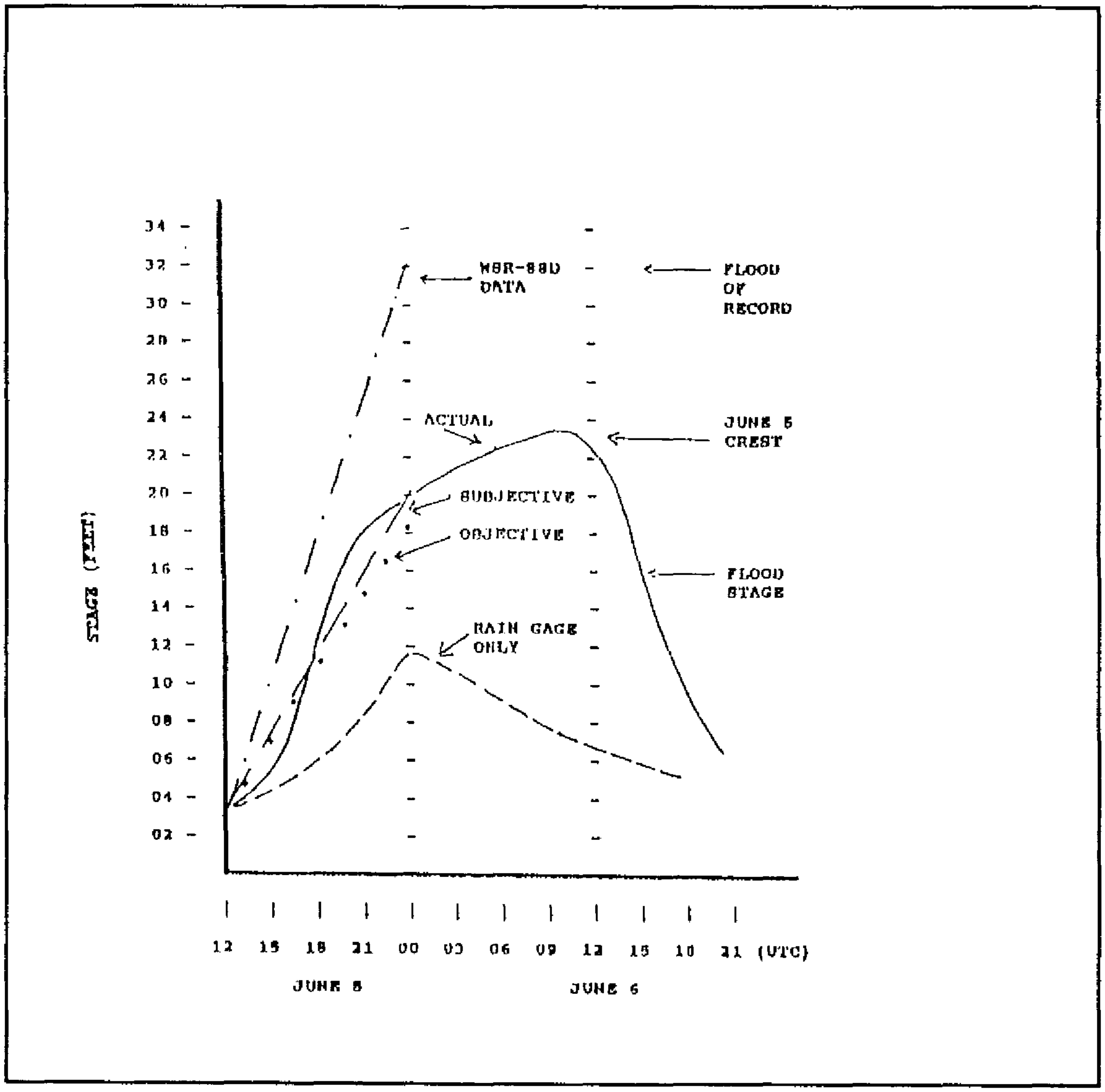


Figure 2. Hydrographs and 12-hour stage forecasts for Bird Creek at Avant, Oklahoma.

First, a weighting factor of 0.57 was determined by using the 4.00-inch observed rainfall at Pawhuska, and dividing that by the 7-inch radar estimate for the same location. This factor was used to correct the radar estimated basin average of 5.2 inches, resulting in a corrected basin average of 2.96 inches. This value was then used to determine a 12-hour stage forecast at Avant of 19 feet, which compared quite well with the actual 12-hour rise (see Figure 2).

A more rigorous method was also used to determine a weighting factor. This method calculated an average bias from the five surface rain gage reports within and around the Bird Creek Basin. Stations A, F, G, I, and J, shown in Figure 1, were used. An analysis of these data indicated a weighting factor of 0.49, resulting in a slightly lower 12-hour stage forecast of 17 feet. It is important to note that other stations were well away from the intense rainfall, and away from reported hail which would bias the WSR-88D rainfall estimates. Although no hail was reported in Pawhuska, reports were received in the general area, making Pawhuska the closest, best "ground truth" of the precipitation event.

It was clear in this event that rain gage reports provided the most accurate measurements of rainfall. However, because gage reports are scattered, they often fail to measure the maximum rainfall. The WSR-88D is capable of locating rainfall maxima, without gaps. But the WSR-88D is subject to biases in estimating actual rainfall totals. Therefore, objectively adjusting the WSR-88D rainfall estimates with surface rain gage reports provides an optimum data analysis.

Stage III Analysis

The National Weather Service River Forecast Centers have now automated this objective method of combining data, where WSR-88D data are available. Called "Stage III Analysis," the method routinely compares rain gage data to WSR-88D rainfall estimates. Since the WSR-88D provides better spatial and temporal detail than available from surface rain gage reports, the final Stage III processing provides a superior analysis to anything previously available in river forecasting.

Conclusions

An analysis of the Osage County flash flood and flood event illustrated several important points. These included the degree to which WSR-88D precipitation estimates are accurate, and where they are most accurate. In addition, it was found that WSR-88D data provided critical spatial and temporal enhancement of surface rain gage data. Also, the characteristics of a thunderstorm, or complex of thunderstorms, can significantly alter the WSR-88D precipitation estimates over areas less than 1500 square miles.

The WSR-88D overestimated precipitation totals for much of Osage County. This was most apparent at Pawhuska where WSR-88D estimates were between 7 and 8 inches, and the rain gage at Pawhuska collected only 4.00 inches. This was likely the result of high radar reflectivity bias caused by hail in the storms.

However, the WSR-88D provides superior spatial and temporal resolution to that of surface rain gage data alone. When the radar data was subjectively combined with the rain gage data, it provided forecasters with sufficient additional information to confidently issue warnings and statements. Now, where WSR-88D data are available, National Weather Service River Forecast Centers use an objective method to combine rain gage data and radar estimates. This method, called Stage III Analyses, provides rainfall data superior to anything previously available.

References

Ahnert, P., M. Hudlow, E. Johnson, D. Greene, and M. Dias
1983 "Proposed "on-site" precipitation processing system for NEXRAD." Pp. 378-385 in *Preprints, 21st Conference on Radar Meteorology*. Edmonton, Alberta, Canada: Canadian Meteorological and Oceanographic Society.

Burnash, R. J. C., R. L. Ferral, and R. A. McGuire
1973 *A Generalized Streamflow Simulation System Conceptual Modeling for Digital Computers*. Sacramento, Calif.: U.S. Department of Commerce and State of California Department of Water Resources.

THE USE OF WSR-88D RADAR DATA AND AN INTERACTIVE HYDROLOGIC MODEL IN FORECASTING A SEVERE FLOOD IN NORTHEAST OKLAHOMA

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National Weather Service Forecast Office, Tulsa

Introduction

Mainstem river forecast responsibility for the Arkansas, Canadian, and Red Rivers in the south-central United States is entrusted to the National Weather Service (NWS) Arkansas-Red Basin River Forecast Center (ABRFC) located in Tulsa, Oklahoma. Specifically, ABRFC's responsibility extends from the headwaters of the Arkansas River near Granite, Colorado, to Pine Bluff, Arkansas; the Canadian River system from eastern New Mexico to Eufaula Reservoir in eastern Oklahoma; and the Red River system from the Texas Panhandle to Fulton, Arkansas. In complement, the National Weather Service Office at Tulsa, Oklahoma, is entrusted with meteorological forecast responsibility and issuances of hydrometeorological watches and warnings for its local service area, which includes all of northeastern and east-central Oklahoma.

Upon the dispatch of a flood forecast by the ABRFC, the appropriate office of the NWS issues the warning and call-to-action information to the emergency management community, the media, and the public. Coordination between state and local officials and the National Weather Service continues throughout the flood event.

Significant changes in operations and technology are currently transpiring in the NWS as it marches toward the new millennium. Two of several programs associated with the National Weather Service's Modernization and Associated Restructuring (MAR) played a vital role in forecasting a severe flood in northeast Oklahoma during September 24-27, 1993. One of these new programs, the 1988 vintage Doppler weather surveillance radar (WSR-88D), augmented the hydrologic forecast accuracy through hourly precipitation estimates.

Radar Data

At each WSR-88D location within the ABRFC, a clock-hour precipitation estimate is created each hour. The radar sends bursts of electromagnetic energy at a maximum frequency of 1,309 pulses per second. As some of this energy encounters rainfall, a portion is reflected and backscattered to the radar. The amount of energy returned to the radar is proportional to the rainfall rate. The returned energy, or reflectivity, is converted to estimated rainfall by using an algorithm that assumes information concerning raindrop size and distribution. The accuracy of the estimated rainfall is reduced when frozen precipitation (hail, sleet, and snow) occurs with rain. The estimation also suffers when drop size and drop distribution are significantly different from what is considered nominal. Biases in the radar derived rainfall fields can be subjectively determined and adjusted for by considering ground truth gage reports. A feature to be implemented with the radar system is the ability to input a maximum of 50 hourly precipitation reports to objectively determine reflectivity bias for each hour and adjust the rainfall estimate. The final hourly precipitation product developed by the radar is referred to as a Stage I precipitation field. While radar derived rainfall estimates are not perfect, the increased spatial and temporal resolution in the data are an enormous improvement over spotty rain-gage reports typically collected at six-hour intervals (or greater) from cooperative observers.

Hydrometeorological Processing

Stage I products are received from 11 WSR-88D radar sites at the ABRFC for Stage II processing. In the Stage II process, all available data is garnered, including satellite imagery and hourly raingage data—further refining the precipitation estimate. Finally, in the Stage III process, a mosaic of hourly Stage II products is generated, quality-controlled, then utilized in the ABRFC hydrologic models. The Stage III process allows for human interaction to "tidy up" the precipitation field, if the need arises. At the ABRFC, the Stage II (and Stage III) processes are conducted in a Unix environment on HP-9000™ workstations running the Stage II and Stage III software.

The Stage III finished product becomes the primary precipitation input into the NWS River Forecast System (NWSRFS). The output generated by NWSRFS is fed into the Interactive Forecast Program (IFP) developed at the NWS Office of Hydrology for MAR-era operations by George Smith, Donna Page, Thomas Adams, and Steve Wiele. During IFP, the hydrologic forecaster interacts directly with the hydrologic model, creating the final hydrologic forecast, which is subsequently issued to the appropriate weather office for public dissemination.

The WSR-88D radar system and the IFP are two of the newest advances in hardware and software technology produced during the NWS Modernization. The WSR-88D hourly-generated precipitation products enable the hydrologic forecaster to rapidly input hourly precipitation estimates into the Interactive Forecast Program, allowing real-time updates of stage forecasts. IFP provides the software framework from which model adjustments to rainfall input, runoff, baseflow, etc., may be conducted. These computer-age tools facilitated rapid evaluation of the hydrometeorological situation that resulted in the prompt issuances of flood forecasts to the appropriate Weather Forecast Office during the flood event of September 24-27, 1993, described below.

The Event

On the morning of September 24, 1993, flash flood guidance values—a reflection of the degree of soil moisture saturation—were quite low. They indicated that a six-hour precipitation event of only 1.0-1.5 inches would result in flash flooding in most of the Lower Neosho River system, while only 2.0-2.8 inches were required for flash flooding in extreme northeast Oklahoma and southwest Missouri. Rain and thunderstorms developed over these areas on the night of September 23 (Thursday night) as a cold front stalled across Oklahoma. The front remained in the area into the weekend and resulted in prolonged rain. Widespread very heavy rains developed Friday night as an upper-level disturbance moved into the plains states and increased the lift near and north of the stalled front.

As precipitation continued throughout the morning of Friday, September 24, 1993, it became apparent that mainstem river flooding unfortunately would also occur. The initial flood forecasts for the Neosho River were issued at approximately 1:40 p.m. Friday afternoon, September 24, 1993, calling for flooding to occur from Leroy, Kansas, to Commerce, Oklahoma, and all intervening forecast points. The degree of flooding would be from "at flood stage" at Leroy, to nearly six feet above flood stage at Commerce, *barring additional precipitation*. Mother Nature was uncooperative, however.

During the evening of Friday, September 24 and early Saturday morning, additional rainfall amounts totaling 6-8 inches were prevalent in southeast Kansas, southwest Missouri, and northeast Oklahoma, with a maximum of nearly 15 inches falling near Pittsburg, Kansas. Forecasts were updated throughout Friday evening, and by Saturday morning, the flood forecast at Commerce, Oklahoma, was subsequently raised to a crest of 22.0-22.7 feet. As additional precipitation data became available throughout Saturday morning, the forecast for Commerce was revised to reflect the river cresting at 23.0-24.0 feet for Monday morning, September 27. One final change to the forecast was made on Sunday, September 26, upping the crest forecast to near 24.5 feet. The Neosho River officially crested at 24.1 feet, over nine feet above flood stage, between 10 a.m. and 4 p.m. Monday morning, September 27.

Summary

Through the use of an interactive hydrologic model, ingesting human-corrected high resolution radar-derived rainfall data, the National Weather Service was able to issue a flood forecast for Commerce, Oklahoma, days prior to the flood crest. This flood crest was the fifth highest to date at Commerce. In nearby Miami, flood damage was severe, with approximately 150 people evacuated in and near the city. The only roadway open in the Miami area at the height of the flood was Interstate 44.

While this flood forecast demonstrated the potential of the new technology, a program to augment the technology, and enhance the NWS's ability to forecast floods has subsequently been started by the NWS field offices serving the ABRFC area. This program, a Quantitative Precipitation Forecast (QPF) program, consists of 18-hour rainfall forecasts that specify areas and amounts in six-hour intervals from 1 p.m. to 6 a.m. local time. Such predictions would likely have given the hydrologic forecasters at the ABRFC the information to issue higher flood crest forecasts even earlier in the event.

The implications of the new technologies and procedures in the NWS to floodplain managers are clear. The increased time and space resolution of rainfall-based digitized rainfall data results in the ability to better survey the water flowing into a particular basin. The obvious benefit is increased lead time on flood events through use of interactive hydrologic models ingesting human adjusted radar rainfall estimates. In addition, this improved means of anticipating inflow into a watershed will allow better management of water release from reservoirs and lakes. This will not only provided better flood management, but also will provide increased information to the managers of hydro-electric generation plants and water resource managers charged with ensuring long-term seasonal water supply.