A UNITED STATES
DEPARTMENT OF
COMMERCE
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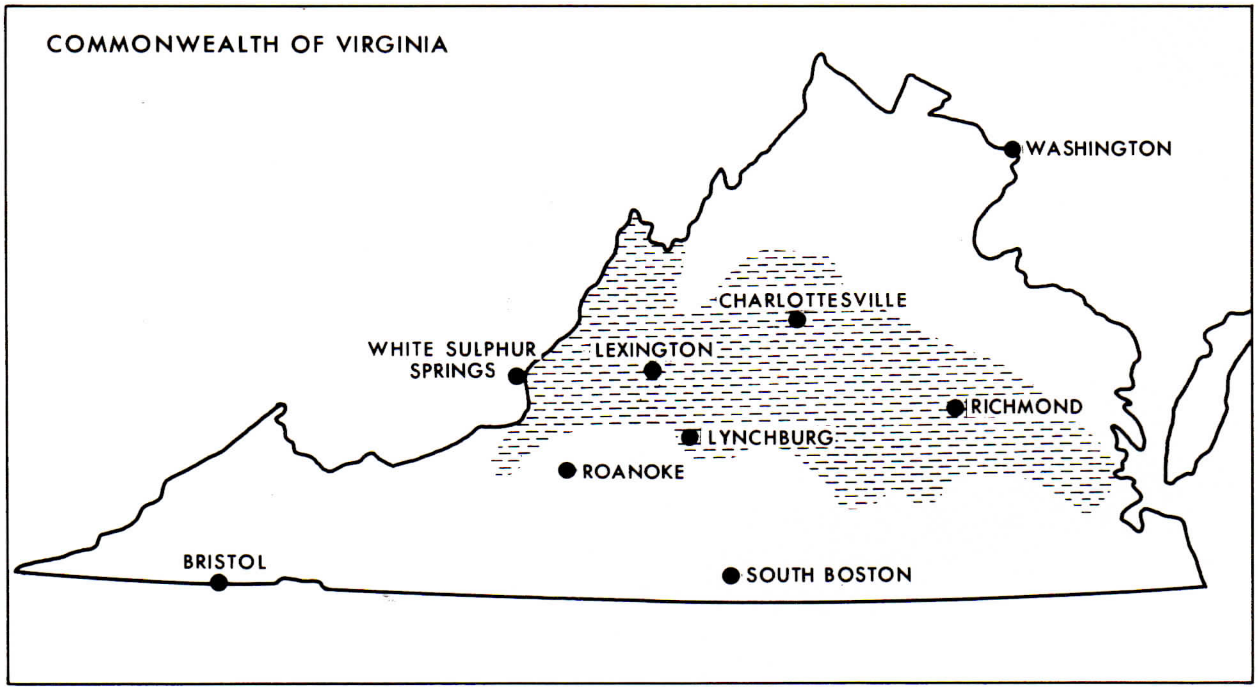
U.S. DEPARTMENT OF COMMERCE
Environmental Science Services Administration

THE VIRGINIA FLOODS

August 19-22, 1969

A Report to the Administrator

September 1969



James River Basin

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FOREWORD

On August 22, 1969, I requested Donald C. House, Chief, Atmospheric Science Services Division, Office of Plans and Programs, to undertake, immediately, an extensive review of the effectiveness of the natural hazards warning system during the period of the devastating flooding in Virginia produced by the remains of hurricane Camille. The purpose of this survey was to establish where the warning system performed effectively and where deficiencies existed that required remedy.

The enclosed report by Mr. House and his group represents their findings on the warning service, its present capabilities, and its limitations. This report reveals clearly the difficulties that must be overcome if satisfactory flash-flood warnings are to be provided for remote areas serviced by limited communications facilities and minimal observing networks. These difficulties can be resolved through the use of emerging technologies such as the automation and satellite capabilities now being developed.

Robert M White

Robert M. White
Administrator
Environmental Science Services
Administration

ESSA/PI690035
September 1969

PREFACE

The survey team included Dr. Harry P. Foltz, Chief, Public Weather and Warning Branch of the ESSA Weather Bureau's Office of Meteorological Operations; Mr. Robert Beck, Deputy Chief, Telecommunications and Space Services Division, ESSA, Office of Plans and Programs; Mr. Marshall Richards, Chief, Hydrologic Services Division of the ESSA Weather Bureau Office of Hydrologic Operations; and Mr. A. S. Kachic, Regional Hydrologist of the ESSA Weather Bureau Eastern Region. Messrs. Beck, Richards, and Kachic, comprising the field survey team, proceeded on August 27, 1969, to the flood-devastated area of Virginia, while Dr. Foltz and I were occupied with ascertaining facts concerning Camille's devastating entry to the United States from the Gulf of Mexico.

The group interviewed Weather Bureau officials, State and local Civil Defense officials, local government officials, representatives of the news media, and the general public to gather facts concerning the adequacy of the warning system and the state of community preparedness.

This report presents the results of the field survey, together with the team's findings and its recommendations for the strengthening of the warning system. The survey team is indebted to numerous individuals within ESSA, other Federal agencies, State and local authorities, representatives of the news media, and the general public for their contribution to this report. It is impossible to enumerate all of them. However, the editorial assistance provided by Mrs. Ann Cook was particularly valuable. The survey would not have been possible without their cooperation and assistance.

D. C. House
Chief, Atmospheric Science
Services Division
Office of Plans and Programs

EXECUTIVE SUMMARY

During the dark hours of the night of August 19-20, a meteorological freak developed over a rural mountainous region of Virginia, an area outside the range of existing radars and between upper-air observing stations.

After striking the Mississippi coastline late on August 17, hurricane Camille had moved inland on August 18 and 19, weakening steadily as it passed over Mississippi, Tennessee, and Kentucky, into West Virginia. Rainfall had diminished from nearly 8 inches in southern Mississippi to 1 to 2 inches in eastern Kentucky. The storm's remnants were forecast to continue on a course through West Virginia, moving into northern Virginia by the morning of August 20. A maximum rainfall of 2 inches was predicted for the Virginia mountains.

Arriving at the Appalachian Mountains in the late hours of August 19, the storm's remnants intensified rapidly and turned to the east. In an eight-hour period, rainfall of 12-14 inches was fairly widespread in the mountains, and amounts exceeding 27 inches occurred in one area. This is more than three times the State's previous record of 8.4 inches in 12 hours, and approaches the all-time rainfall records in the United States. The now-intensified remains of Camille moved eastward across Virginia, leaving rains of 4 inches or more in its path across the state.

More than 100 people are known to have perished in the ensuing floods in the James River Basin, most of them in the flash floods that devastated the mountain areas before dawn broke on August 20. Telephone lines were destroyed by the flood waters and landslides, preventing river and rainfall reports from reaching Weather Bureau offices. In the hardest-hit region, only one officially established community flash-flood warning system existed. Warning actions were limited to attempts by police, local officials, and volunteers to alert and evacuate people in the path of the flood waters.

The first Weather Bureau statement that indicated the seriousness of the night's events was issued by the Washington Forecast Office at 3:39 a.m., August 20, reporting heavy rains and flooding in west and central Virginia and southern West Virginia. Later in the day, the Bureau began issuing crest forecasts for points on the middle and lower reaches of the James River. These predictions were as timely and accurate as the available data allowed, and gave sufficient time and information for communities to take the necessary flood-control actions.

The ESSA survey team evaluated the performance of the river and flood forecast and warning service, and the state of community preparedness. In general, the team concluded that:

—*meteorological observations were inadequate to forecast or to detect the intensification of the storm.*

—*a nearly total breakdown in the river stage and rainfall reporting network made it impossible to describe the area and intensity of precipitation over the James River Basin.*

—the existing network, had it remained in operation, would have given a true picture of rainfall amounts and distribution.

—with a single exception, no community flash-flood preparedness programs existed in the headwaters of the James River Basin.

—flood forecasts for the middle and lower reaches of the James River were as accurate as could be expected on the basis of the data available.

To correct the defects in the river and flood forecast service, the survey team recommended that:

—the present system for collecting and transmitting river and rainfall data, which is largely manual and overly dependent on the human element, be modernized as quickly as possible. To this end, it is recommended that an up-to-date data-collection system, incorporating the latest advances in sensing and communications technology, be developed to assure reliable data, as recommended in "ESSA and Operation Foresight," May 1969.

—the rainfall and river gage reporting system using the ESSA Geostationary Operational Environmental Satellite (GOES) relay capability, initiated in the FY 71 budget, be pursued vigorously, to assure that reliable reports are available in near real time to alert the hydrologic system to heavy rainfall, to furnish key river-stage readings, and to serve as "truth" reference points for radar-derived estimates of the areal distribution of rainfall.

—in areas where the regular surface weather-observing network is inadequate to detect and describe intense storms the size of Camille, gaps be filled with a simple, reliable automatic weather station such as the Weather Bureau's AMOS III–70, and that this type of equipment be used to cover periods when regular manned observing stations are not in operation.

—WSR–57 radars be installed in the Bristol and South Boston, Va., areas and the Washington radar operation moved to Patuxent River, as currently planned, to bring radar coverage in Virginia to a level which will give a high degree of assurance of detecting heavy rainfall and severe local storms.

—a prototype radar digitizing system to transmit the large volume of data from radar locations to River Forecast Centers in near real time to be procured and tested for operational suitability to determine if the system, and computer programs to relate radar data and "truth" reference rain gages, will meet the needs of the Hydrologic Services System.

—a flash-flood warning system based on the weather radar network be implemented in 20 States along the Atlantic and Gulf coasts and inland about 300 miles. The system should include:

> *—automatic rainfall reporting networks, with a minimum of 450 gages, located around 11 existing and planned radars; and*
>
> *—flash-flood warning devices installed upstream from at least 50 communities to provide warnings where other techniques will not suffice.*

—arrangements be made to obtain cloud pictures from NASA's geostationary satellite ATS–3 in real time at the National Environmental Satellite Center and to initiate real-time watch and interpretation of these pictures for storms such as Camille.

—action be taken to improve knowledge of the genesis, growth, and dissipation of small-scale systems, leading to better description, understanding, and prediction of related weather phenomena; the increased knowledge then be applied to the improvement of observation, processing, and prediction subsystems, and that ESSA establish as its goal the redefinition of these subsystems by 1975.

—instructions in the Weather Bureau Operational Manual be reviewed to assure that: (a) reports of potentially hazardous conditions received from cooperative observers or other reporting sources are promptly brought to the attention of a responsible professional-level employee in those offices where 24-hour coverage by professionals is not possible; and that (b) reports of this type are relayed promptly and directly, by the fastest means available, to the responsible forecast office.

—the Washington River Forecast Facility be placed under the administrative and operational control of the Director, Weather Bureau Eastern Region, as soon as possible. Plans for consolidating the Washington, D. C., and Harrisburg, Pennsylvania, centers reflected in the FY 71 budget should be continued, but correction of the organizational anomaly should not be contingent on the FY 71 budget action.

—Weather Bureau Operations Manual, Part C, Chapter 41, be revised to require that Warning Coordination Centers continue to issue bulletins on a tropical cyclone so long as it or its remnants constitute a recognizable low-pressure center or rainfall area within the United States and its coastal waters.

—ESSA, in cooperation with the Office of Emergency Preparedness and State officials, attempt to strengthen the community-action flash-flood program, providing sufficient staffing in Weather Bureau offices to develop and establish the local warning system.

—a flash-flood alarm system—in which a detector located upstream from the community causes an alarm to sound in the police station or other location when the stream reaches a danger level—should be incorporated in the community-action program. The system is estimated to cost $2,500 installed.

—ESSA consider a joint effort with NASA to investigate the feasibility of a natural disaster direct-broadcast satellite to relay warnings to the wide segment of the population not now reached directly by the warning communications system.

—research and development activities aimed at more timely and accurate river forecasts be continued. Emphasis should be given to developing hydrologic models and related computer programs which will continuously simulate streamflow from rainfall and river-stage reports.

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Chapter I

The Storm

The eye of Hurricane Camille moved inland just east of Bay St. Louis, Mississippi, on the night of August 17, 1969. It has been estimated that gusts of at least 190 mph hit the city, while winds of 150 mph or more raked the area east to Biloxi. Camille weakened as she moved inland on a curving path through Mississippi, Tennessee, Kentucky, and West Virginia during the 17th, 18th, and 19th of August. The heavy rains normally accompanying a dying hurricane's path over land diminished from amounts approaching 8 inches in southern Mississippi to 1-2 inches in eastern Kentucky as the storm passed. Figure 1 shows the storm's path from the 17th to the 20th of August 1969.

During the evening of the 19th and early morning of the 20th, the remnants of Camille intensified rapidly as she crossed the Appalachian Mountain ridges. The gentle rains that had fallen in Kentucky without causing significant flooding became, in the space of a few hours and tens of miles, a torrent of rain that spread eastward across southern West Virginia and west central Virginia during the evening, merging with a band of heavy showers and thunderstorms that had moved into Virginia from the north and northwest earlier in the afternoon and evening. By about 10 p.m. EDT, August 19, a band of rain and thunderstorms some 40-50 miles wide extended in a general east-west orientation from the vicinity of White Sulphur Springs, West Virginia, to Fredericksburg, Virginia. Near midnight, the low pressure center began to intensify as it moved eastward into Virginia along a track south or Roanoke and Lynchburg. Rainfall to the north and east of the low pressure center increased very rapidly along the western slopes of the Blue Ridge Mountains, with more than 10 inches accumulating at Clifton Forge, Virginia. The rainfall continued to intensify on the eastern slopes of the Blue Ridge Mountains where it reached catastrophic cloudburst proportions.

Results of a post-storm survey by Weather Bureau personnel show that rainfall of 12-14 inches was fairly widespread in Nelson County and the southern part of Albemarle County, with reliable indications of 27-28 inches in the central part of Nelson County. Rainfall in excess of 4 inches fell over an area 30-40 miles wide and more than 130 miles long, as the storm moved eastward across Virginia on August 20, 1969. Figure 2 shows the rainfall as determined from post-storm information.

This rainfall caused extensive flash flooding in Albemarle, Allegheny, Amherst, Bath, Botetourt, Buckingham, Cumberland, Fluvanna, Goochland, Nelson, Orange, Powhattan, and Rockbridge counties. The flash flooding reached disaster levels in Rockbridge, Amherst, Nelson, Albemarle, and Fluvanna counties. On the Tye and Rockfish River watersheds in Nelson County where the greatest rainfall occurred, the flash flooding and rain-induced landslides caused a major disaster. Figure 3 shows these flooded areas.

Flash flooding on the headwater streams and tributaries of the James River early on August 20, 1969, was followed by record flooding along the main stem of the river as far as Richmond where the tidal estuary begins. As shown in Figure 1, the now-intensified remnants of Camille moved rapidly eastward across Virginia and into the Atlantic Ocean on the 20th, regaining tropical storm winds of 65-70 mph on August 21st.

The rains, flash floods, and rain-induced landslides accompanying the storm's passage were revealed in the next few days as the worst natural disaster ever to strike Virginia. As of September 8, 1969, the State had counted 107 dead and 102 injured, with 55 persons still missing. According to Civil Defense officials in Virginia, damages have been tentatively set at $113 million, with long-term losses of farmland and industrial production yet to be assessed. Cost of protective measures at downstream locations

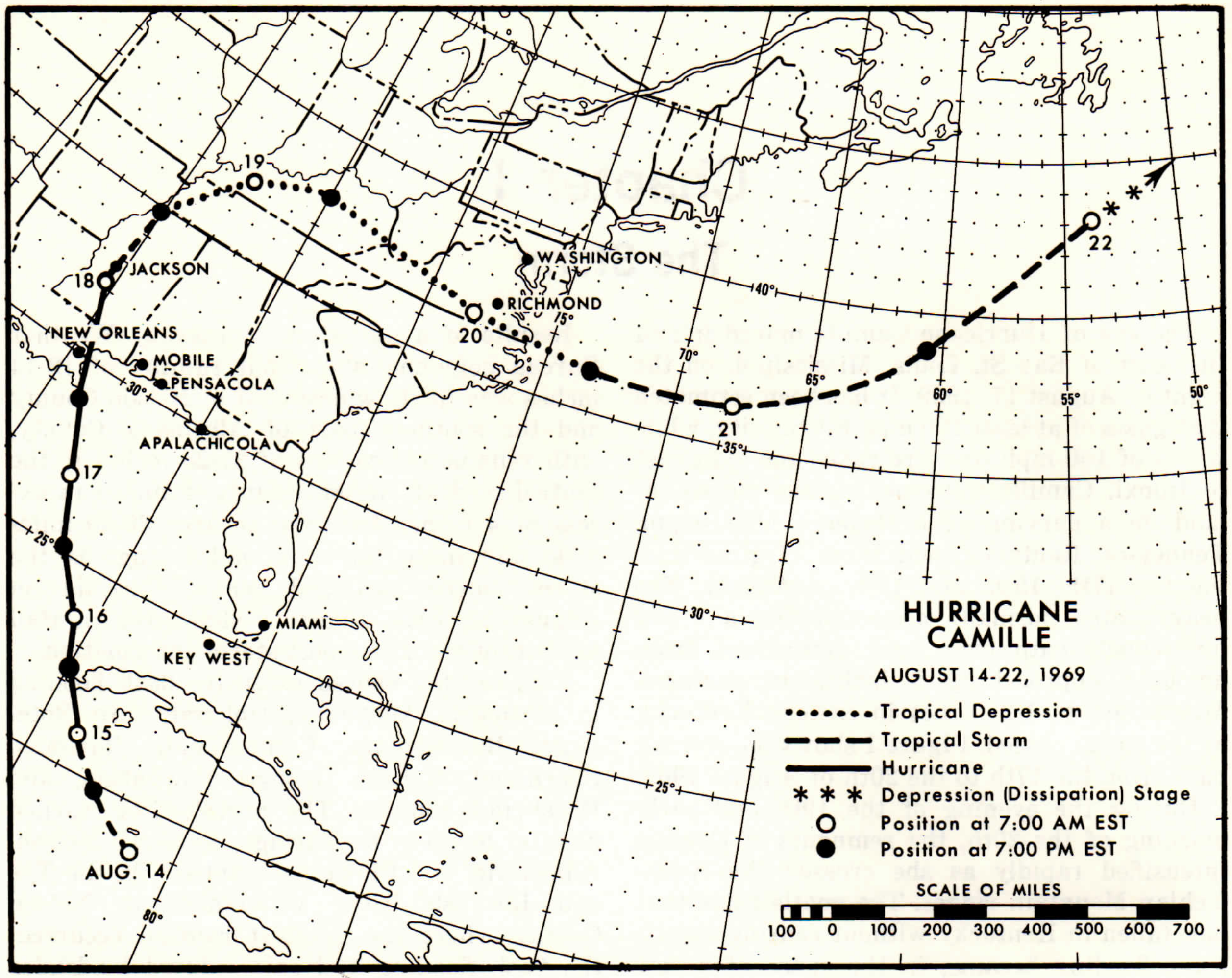


Fig. 1—Hurricane Camille Track, August 14-22, 1969

on the James River also remains to be determined, as do the costs for rescue and disaster relief work of State and Federal agencies.

The 27-28 inch rainfall within about 8 hours in Nelson County, Virginia, represents one of the all-time meteorological anomalies in the United States.* A study made by the Weather Bureau in 1956 for the Corps of Engineers concluded that the probable maximum rainfall possible in this area was 28 inches in 6 hours and 31 inches in 12 hours. The previous record rainfall in Virginia was 8.4 inches in 12 hours at Big Meadows on the Skyline Drive, associated with a hurricane in 1942. For purposes of comparison, this catastrophic 27-28 inch rainfall approaches the following records:

12 inches in 42 minutes at Holt, Mo., in 1947

19 inches in 2 hours, 10 minutes at Rockport, West Virginia, in 1889

22 inches in 2 hours, 45 minutes at D'Hanis, Texas, in 1935

31 inches in 4 hours, 30 minutes at Smethport, Pa., in 1942

34 inches in 12 hours at Smethport, Pa., in 1942.

* The Geological Survey subsequently has reported a 31 inch rainfall measurement in the same area of Nelson County.

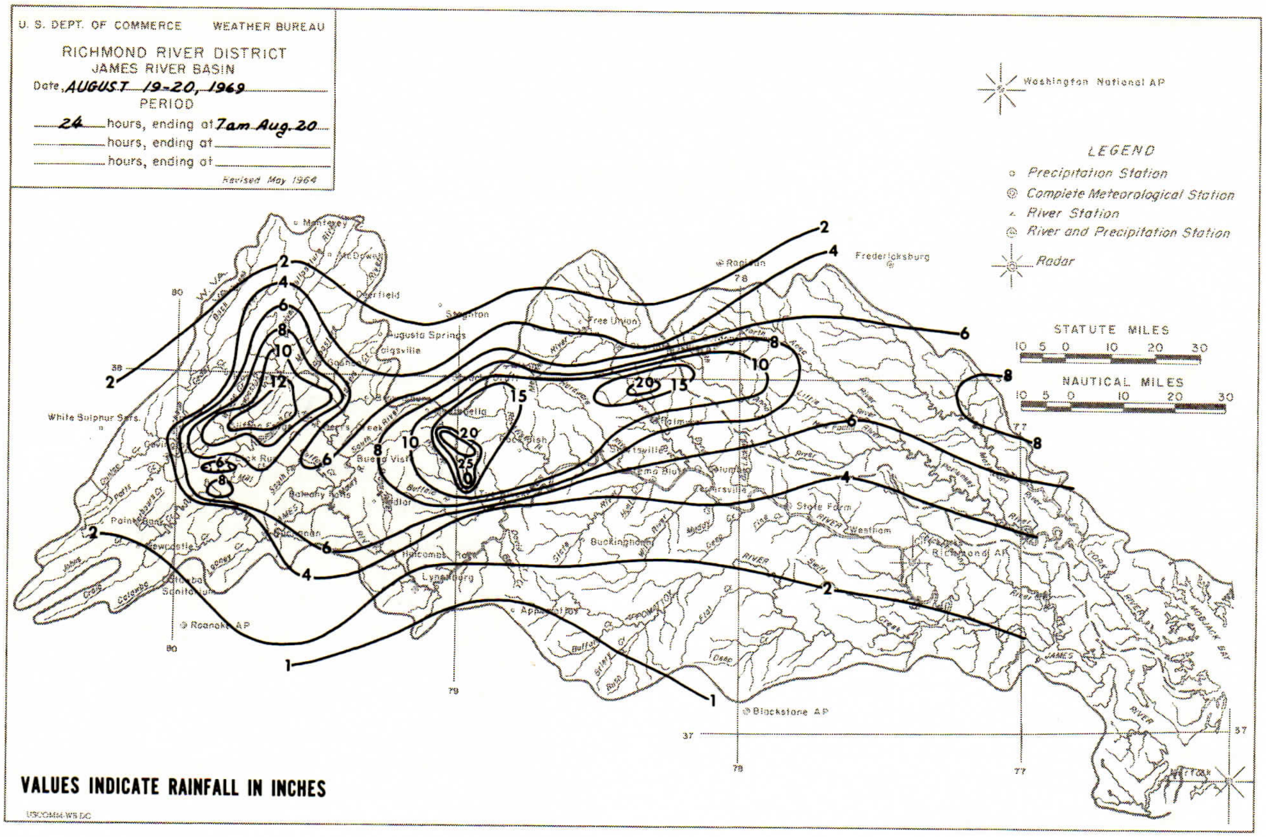


Fig. 2—Rainfall as Derived From Post-Storm Survey

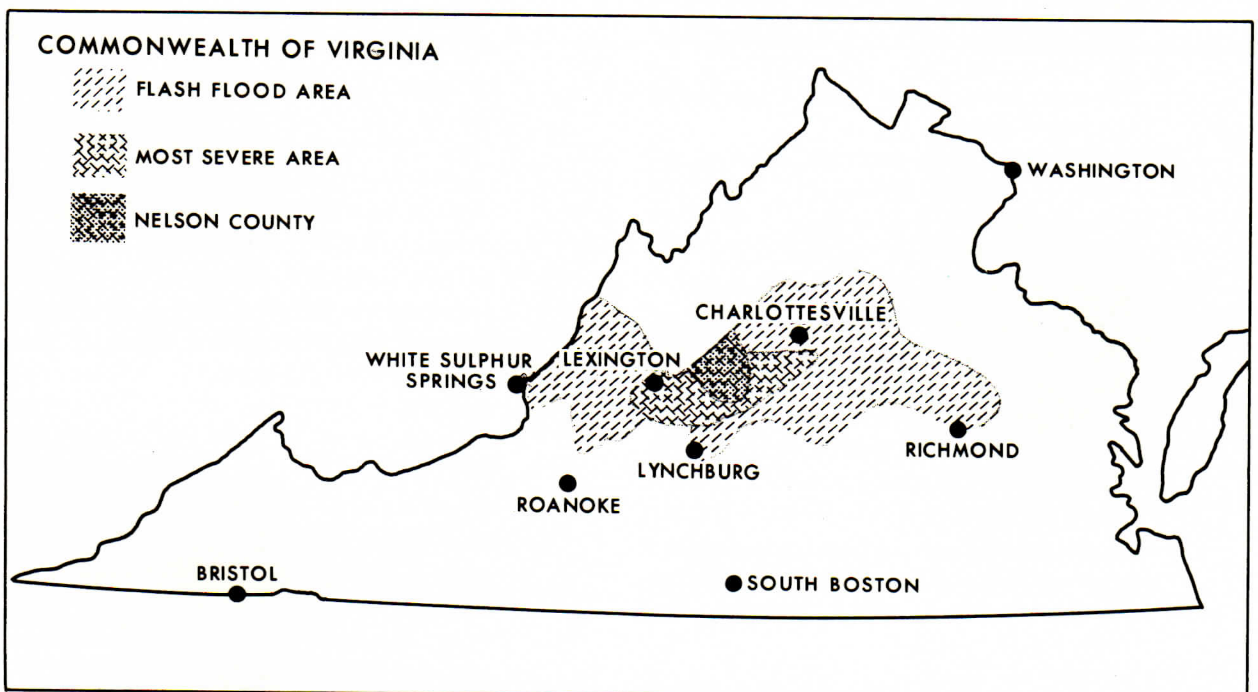


Fig. 3—Areas Flash Flooded August 19-20, 1969

Chapter II

Preparation and Warnings

A. The River and Flood Services

The broad-scale objective of the river and flood services of the ESSA Weather Bureau is to provide a single, authoritative source of forecasts and warnings for the protection of life and property and for efficient management of water-control structures. To carry out the responsibilities for river and flood forecasting and warning in keeping with this objective, the Weather Bureau has both meteorological and hydrologic systems to acquire and collect data, process data, and prepare forecasts and warnings. The significant features of the two systems applicable to Virginia are as follows:

1. The Meteorological System.
   - (a) National Meteorological Center (NMC) provides synoptic-scale meteorological guidance material along with basic analyses and forecasts for the entire Weather Bureau organization. Its Director reports to the Director of the Weather Bureau.
   - (b) Washington Forecast Office is responsible for meteorological forecasts and warnings for the States of Delaware, Maryland, West Virginia, and Virginia, including guidance material for Weather Bureau offices in these States. The office functions as a Hurricane Warning Office responsible for issuing hurricane advisories and bulletins based on forecast guidance from the National Hurricane Center, and as a Warning Center to coordinate the release of public warnings on hazardous weather. The Meteorologist in Charge reports to the Director, Weather Bureau Eastern Region.
   - (c) Richmond Weather Bureau Office is responsible for forecasts and warnings for most areas of central and western Virginia, excepting counties in the immediate vicinity of Lynchburg and Roanoke. The Meteorologist in Charge reports to the Director, Weather Bureau Eastern Region.
   - (d) Lynchburg Weather Bureau Office is responsible for forecasts and warnings in Amherst, Appomattox, Bedford, Charlotte, Halifax, and Pittsylvania counties during its hours of operation (6 a.m.-7 p.m. EDT). When it is closed, this responsibility passes to the Roanoke Weather Bureau Office. The Meteorologist in Charge reports to the Director, Weather Bureau Eastern Region.
2. The Hydrologic Services System.
   - (a) Washington River Forecast Facility is responsible for preparing river forecasts for the Potomac, Rappahannock, James, and York rivers and tributaries and local Chesapeake Bay drainage in Maryland and Delaware. It provides River District Offices in Washington and Richmond with basic river and flood forecasts. This facility is unique within the hydrologic services system in that it functions as a River Forecast Center but is organically assigned to the Hydrologic Research and Development Laboratory under the Associate Director of the Weather Bureau for Hydrology. All other centers are responsible to a Weather Bureau Regional Director.
   - (b) Richmond River District Office is responsible for collecting river and precipitation reports and issuing flood warnings and forecasts for the James and York river basins. The River District Office functions are a part of the service responsibility of the Richmond Weather Bureau Office, and the Me-

teorologist in Charge reports to the Director, Weather Bureau Eastern Region.

(c) Lynchburg Weather Bureau Office is responsible for collecting hydrologic data and distributing river forecasts and warnings for the upper James River basin when the office is open. When it is closed, the responsibilities revert to the Richmond River District Office, and all cooperative observers switch their reporting to Richmond.

River and flood information is distributed to the public in several forms. Routine weather forecasts contain information on expected rainfall. When a major storm is in progress, bulletins are issued by Warning Coordination Centers to alert the public to the situation. Public statements are issued by local Weather Bureau offices to supplement these bulletins or to cover a storm situation when bulletins are not being issued. Flash-flooding information is included in these various meteorological issuances. Flood-stage forecasts and crest-stage forecasts are issued by River District Offices for specific points along a river and its major tributaries, in the form of public statements at about 6-hour intervals.

B. Community Preparedness

On small streams, especially near the headwaters of river basins, heavy rains may cause water levels to rise quickly, creating a flash flood. Swift action is essential to the protection of life and property. The Weather Bureau has helped set up flash-flood warning systems in about 100 communities throughout the United States. In these community-action programs, a volunteer network of rainfall and river observing stations is established in the area, and a local flood warning representative is appointed to collect reports from the network. The representative is authorized to issue official flash-flood warnings based on a series of graphs prepared by the Weather Bureau. These graphs show the local flooding that will occur under different conditions of soil moisture and rainfall. On the basis of reported rainfall, the representative can prepare a flood forecast from these graphs, and spread a warning within minutes.

A flash-flood community action program was in existence at Covington, Va. This program, established in 1958 under the guidance of the Meteorologist in Charge of the Richmond Weather Bureau Office, uses the facilities of the city and the West Virginia Pulp and Paper Co. Reports from a river gage and rainfall gage in the city and from a city-funded cooperative observer upstream are normally supplemented by reports from other cooperative observers' rainfall gages in the area when the Covington readings are telephoned to Lynchburg or Richmond. In this storm, the supplemental reports were not available because of telephone service breakdowns, and the crest forecasts prepared by officials of the Covington community program were therefore in error. However, the river gage readings alerted the city to the rising waters, and necessary evacuations were completed without loss of life.

No other formally organized flash-flood community program had been established in the flood area; however, the cooperative arrangement between the city of Buena Vista, Va., and the Weather Bureau, in which readings from the river gage (located about 3 miles upstream) are remoted into the police station, was an important factor in alerting the city to impending flooding of the Maury River.

The Meteorologist in Charge at Richmond, in whose area of responsibility the flash flooding occurred, indicated several reasons why there are so few organized community flash-flood programs in the area. First, the low incidence of really destructive flash flooding, over and above that normally expected with the thunderstorms prevalent in the mountainous areas, makes it difficult to convince public officials of the need to spend money on such a program. Second, the limited staffing in the Richmond Weather Bureau Office and the increasing demands on his time as Meteorologist in Charge and State User Services Representative precluded his taking the large amount of time that would have been needed to visit and sell, and then plan and supervise, community flash-flood programs. Third, the travel necessary for a Statewide flash-flood program has not received sufficient priority in recent years.

Other considerations limiting any effort to expand community flash-flood warning systems in Virginia include: lack of staff time at the River Forecast Facility for the required forecast procedure development; and lack of the necessary instrumentation for additional systems.

C. Specific Actions

The only specific advance actions by ESSA components were taken by the Weather Bureau Eastern Region Headquarters. At about noon on Tuesday, August 19, 1969, the Regional Director noted that the remnants of hurricane Camille still posed a significant rainfall threat and directed his Regional Hydrologist to alert the River Forecast Centers in the path of the storm. Centers at Cincinnati, Pittsburgh, and Harrisburg were alerted on the basis of the forecast movement of the storm and rainfall. The Washington River Forecast Facility was not alerted because its area was not forecast to be significantly affected.

The flash flooding which followed by a matter of minutes the onset of torrential rain in the upper and middle reaches of the James River Basin precluded any effective community preparedness actions. Warnings were limited to efforts by police, public officials, neighbors, and relatives to alert residents to the rising water. These attempts were hampered by water- and debris-covered roads and washed-out telephone lines.

Many communities on the James River and the larger tributaries experienced two floods. A flash flood from their local streams was followed by a second flood, 1 to 12 hours later, when upstream floodwater arrived.

In the lower reaches of the James River where warnings of impending flooding were issued as much as 8 hours in advance, community preparedness actions were possible. At Richmond, where warning of flooding had a leadtime of more than 24 hours, the city put its flood plan into effect. Existing flood-control dikes were closed, and the threatened areas evacuated. A substantial area of the city bordering the river was flooded, however, when it became necessary to abandon a pumping station because of threatened failure of sandbagged walls. This allowed water to back into the city through sewers and drains.

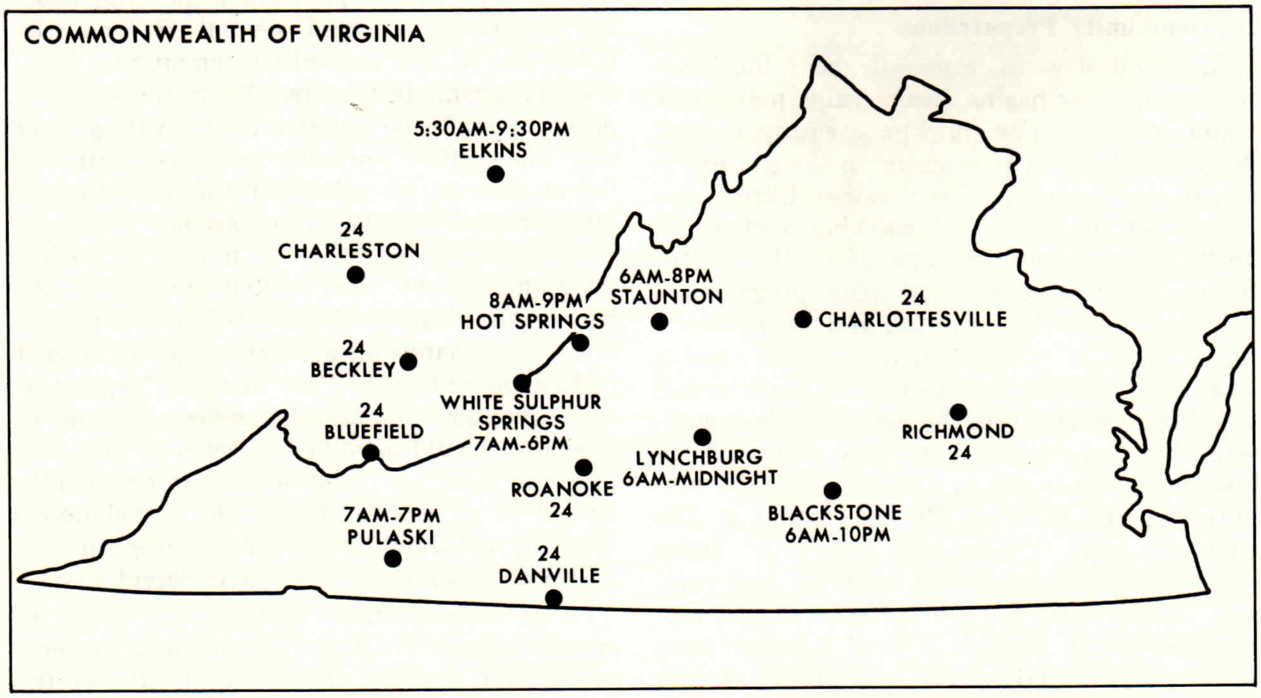


Fig. 4—Hourly Reporting Stations, West-Central Virginia and Southern West Virginia

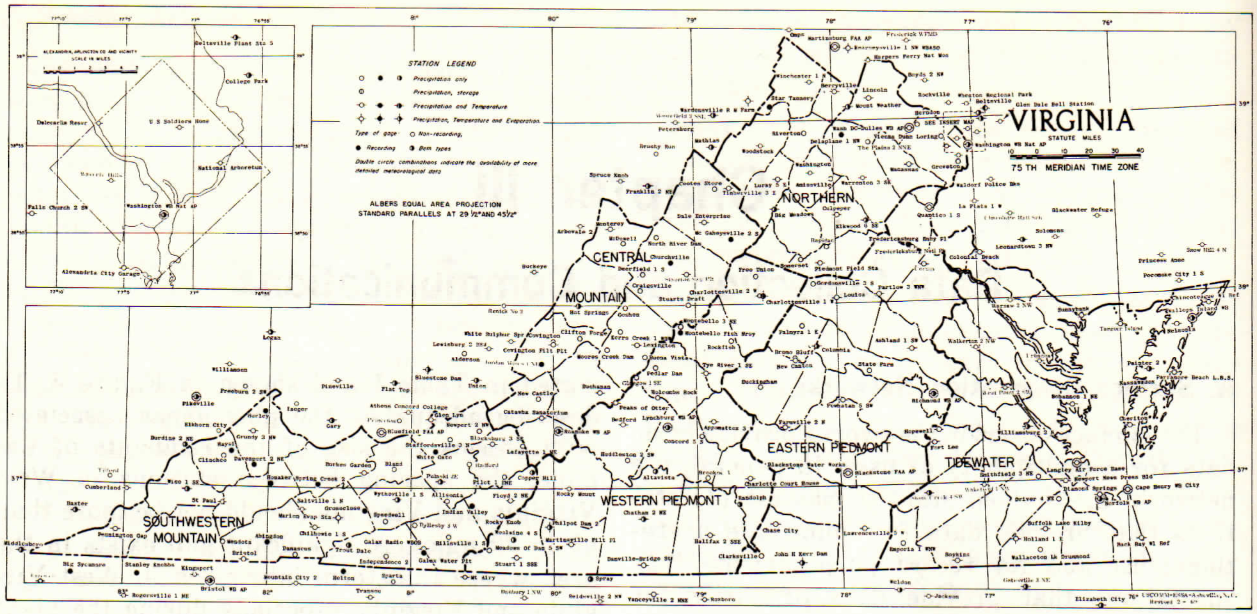


Fig. 5—Substation Network in Virginia

raw data for flood control and flood forecasting. For the most part, the observations are collected and compiled into published summaries. Provision is made, however, for selected substations to report by telephone or telegraph to a specified River District Office whenever rainfall in a 24-hour period exceeds 0.5 inch at 1 a.m., 7 a.m., 1 p.m., or 6 p.m., and to continue reporting every six hours thereafter so long as that rainstorm continues. Token payments are made to substation observers for taking and reporting rainfall measurements, and additional payments of $0.60 are made for each special observation transmitted to the River District Office.

In addition to the network of regular reporting stations and the selective-reporting substations, the Weather Bureau—on its own and in cooperation with Federal, State, and local agencies and industries—has a network of river-stage reporting stations. Some of these river gages are telemetering—that is, they may be interrogated by telephone from a River District Office—but most require that a cooperative observer read the gage (this may involve traveling a few hundred yards or several miles) and telephone his report to the designated Weather Bureau office. Figure 5 shows the location of substations in Virginia.

There were 28 rain gages and 14 river gages in the James River Basin reporting network. Six of the 14 river gages were telemetering types, but only 2 were in the area of flash flooding. The accompanying map (Figure 6) shows the location of the rainfall and river gages, as well as the rainfall reports available to the River Forecast Facility for use in preparing the forecasts issued on August 20, 1969.

Many of the stations, particularly in the Tye and Rockfish river basins, did not report. Subsequent surveys by Weather Bureau personnel revealed that most of the reports were missing because the equipment had been damaged or destroyed, telephone lines were out, or observers couldn't get to the gages. This survey also brought to light the fact that available reports did not describe adequately the rainfall in the area. The analysis of the reports used by the River Forecast Facility is shown on the map and indicates a wide area of 6-8 inches of rainfall between Palmyra and Kerrs Creek. This was in fact the area of maximum rainfall, with amounts in excess of 12 inches over most of the region and peak values of 27-28 inches south and east of Montebello.

River-stage reports were received from 8 of the 14 river gages; however, one report from Holcombs Rock was in error by about 20 feet. This gage, owned by the Appalachian Power Company, is remoted to the company's Roanoke office where it is read and reports sent to Lynchburg or Richmond. Subsequent checks revealed

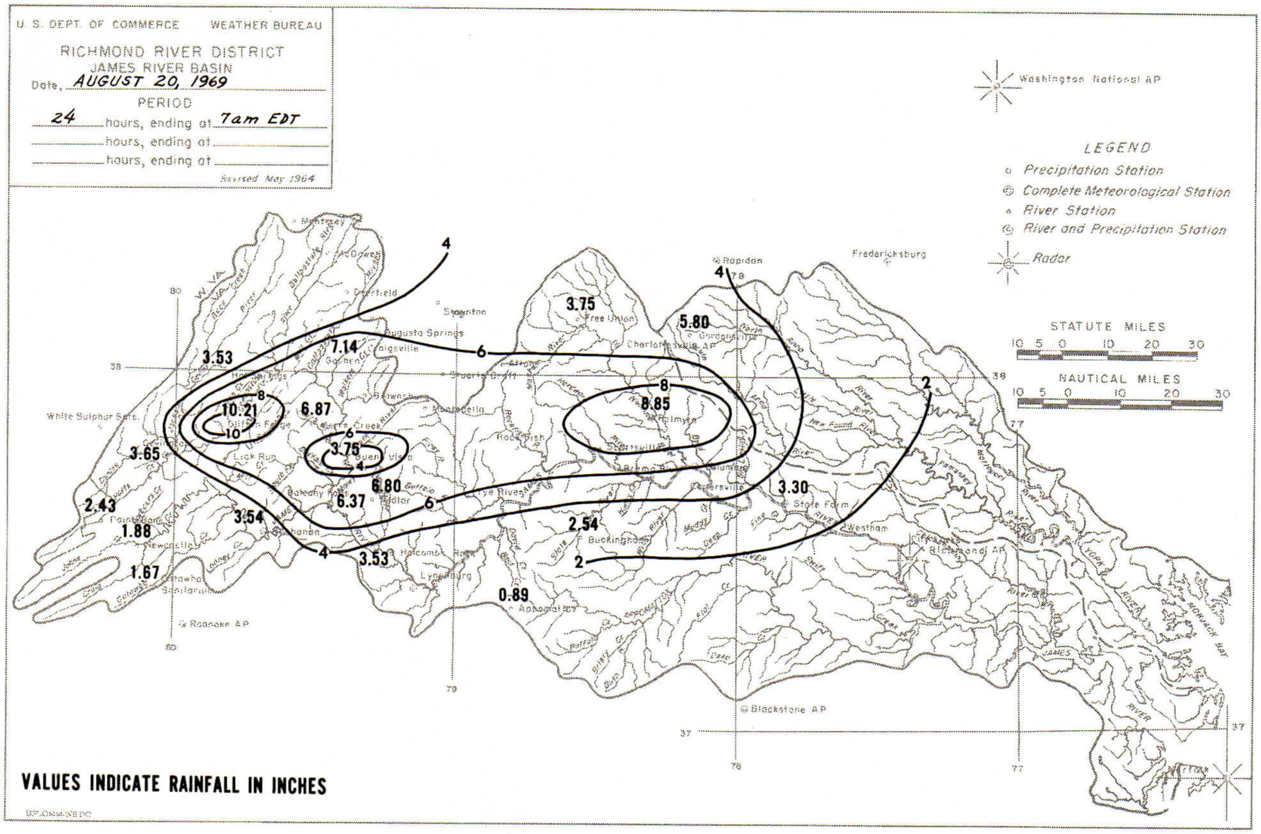


Fig. 6—Rainfall Reports Available at Noon August 20, 1969, and Used in First James River Forecast

that the erroneous reports were made by an inexperienced observer who misread the complex recorder and repeated the error throughout the morning. The erroneous report of a 47.5-ft. stage was finally discarded by the River Forecast Facility, since it indicated catastrophic flooding and there were no confirming reports above or below the gage. A telephone call to Roanoke finally resolved the problem.

In summary, rainfall and river-stage reports were fragmentary and usually delayed, and many were never received. Although instructions provide for 1:00 a.m. reports, only one was received. The greatest single deficiency was the inability to obtain near-real-time river reports and rainfall data. To provide an effective forecast and alarm service, reports need to be obtained from a large percentage of the total basin at the same time. A reliable automated data-collection system would have provided downstream locations 6 to 12 hours' more warning than was actually given. Flash-flood alarm devices coupled to warning sirens might have given advance warning to those communities hit by the flash flooding.

B. **Upper-Air Observations**

Upper-air observations include measurements of pressure, temperature, water vapor, and wind direction and speed at various levels in the atmosphere from the surface up to about 100,000 feet. The principal method for gathering upper-air data is the rawinsonde observation. These are taken at 94 ESSA ground stations and 38 other cooperative and special project station locations (financed by Department of Defense), and by 15 moving ships, including merchant, Military Sea Transport Service, and ESSA Coast and Geodetic Survey vessels.

In the southeastern United States, land-based upper-air stations in the path of Camille are spaced 180 to 300 miles apart (see Figure 7) and take observations at 12-hour intervals. This is considered adequate for the description, analysis and prediction of large-scale motion systems such as mid-latitude cyclones. This network is insufficient, in terms of number of stations and frequency of observations, to detect the significant atmospheric events that led to the reintensification of the storm. The rein-

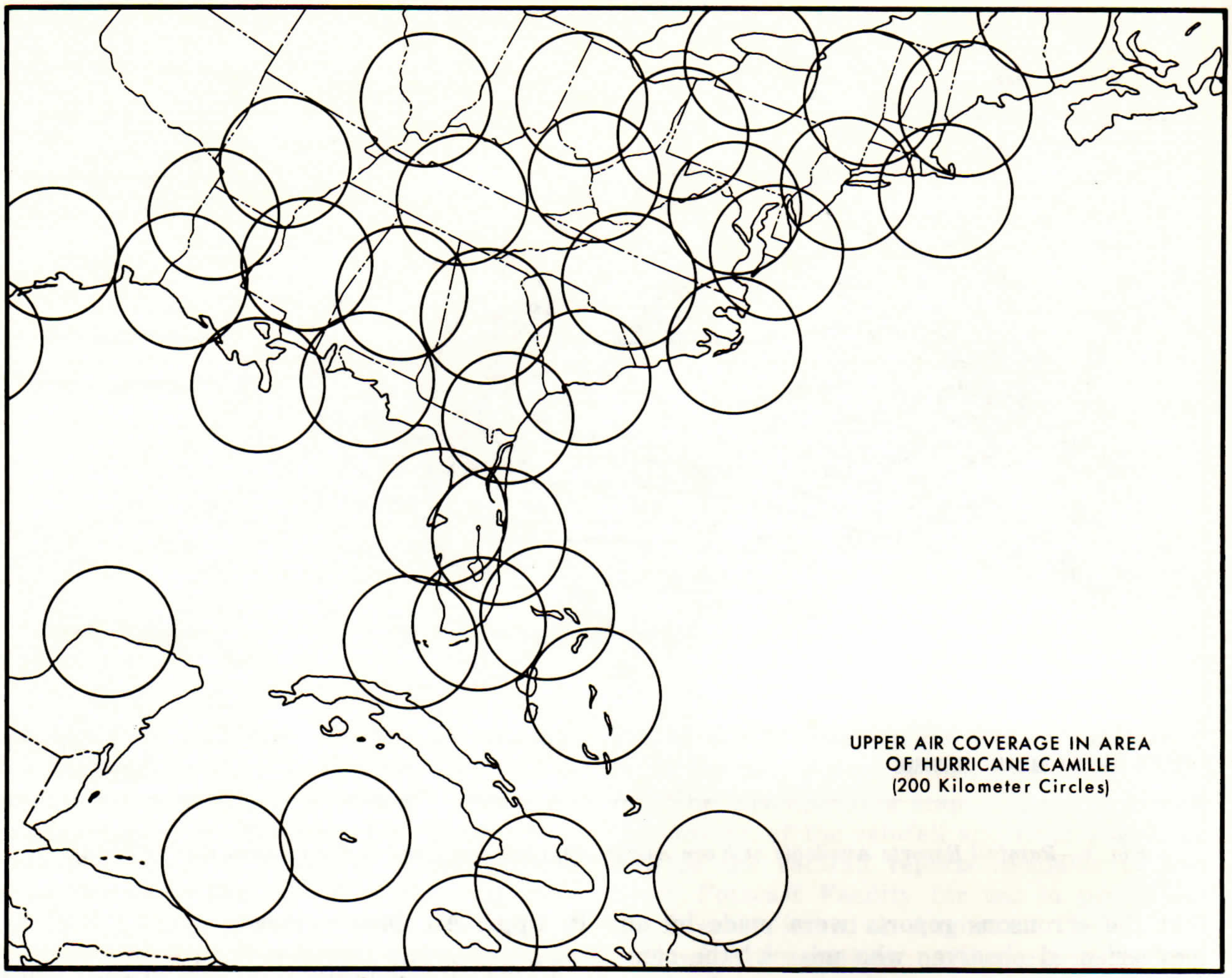


Fig. 7—Upper-Air Coverage in Area of Hurricane Camille

tensification occurred between observation times, and the atmospheric motion system was on a scale too small to be detected by the existing stations.

C. Weather Radar Observations

Modern weather radars such as the WSR-57 detect precipitation, making it possible to estimate precipitation amounts as well as to identify and track squall lines, hurricanes, tornadoes, and other severe storms. They provide systematic observation of the location, height, and estimated intensity of precipitation. Radar reports are made hourly when precipitation is observed within about 125 miles of the radar, and more frequently when conditions indicate severe storms or rapidly changing weather. Local use radars with more limited range provide information for short-period forecasts and warnings in the immediate area.

The WSR-57 radar at Washington National Airport was the only modern Weather Bureau radar which might have detected the heaviest rain. However, its ability to detect precipitation in the direction of the storm is limited by obstructions in the vicinity of the antenna, and the heaviest rainfall was well beyond the most effective range of the radar. Only the northern portion of the storm area was observed. Thus, the radar observer had no information on the extent of the heavy rain, but he did maintain effective and frequent telephone contact with the guidance forecaster at the Washington Forecast Office, keeping him apprised of conditions within about 125 miles of Washington, D.C. During the afternoon of August 19, before the heavy rain in Virginia, there had been coordination between the Hydrologic Service Specialist at the Washington River District Office and the radar observer, but the area that

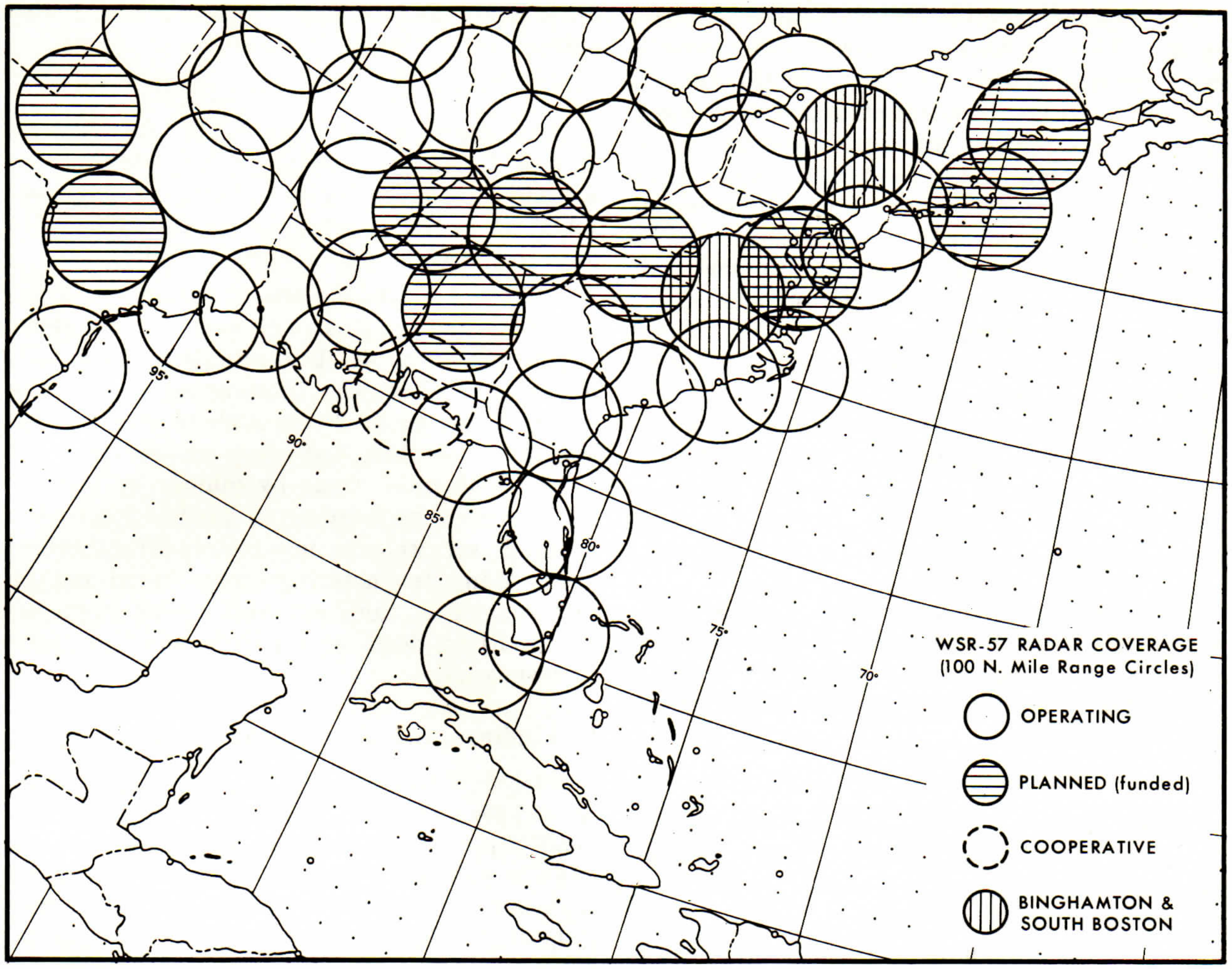


Fig. 8—WSR-57 Radar Coverage

concerned them was in Pennsylvania where the remnants of Camille were forecast to move during the night.

The local use WSR-3 (an obsolete World War II surplus bombing radar) at Richmond was operating through the storm, but the radar is limited in range and power and does not have the capability for measurement of storm intensity. It therefore detected only the eastern portion of the rainfall and could not indicate the seriousness of the situation.

At Norfolk, Va., the Weather Bureau has a repeater display attached to the FAA air traffic control radar, but this radar could not be used effectively because of the limited 60-mile range.

Effective radar coverage does not exist in western and central Virginia. Figure 8 illustrates the present network in the southeastern United States and those stations which are to be added. The new radar planned (and funded) for the Bristol area, plus another radar planned for South Boston, Va., and relocation of the Washington radar operation to Patuxent River Naval Air Station, will bring radar coverage in Virginia to an acceptable level.

D. Environmental Satellite Data

Pictures from ESSA 8, an Automatic Picture Transmission satellite, at mid-morning on the 19th of August, showed no unusual features in the cloud structure associated with Camille. These pictures are available to the Washington Forecast Office, but are not transmitted to Richmond or Lynchburg. Pictures from ESSA 9, a stored-data satellite, taken early in the afternoon of the 19th and available to the Washington Forecast Office about 8:30 p.m. EDT, similarly showed no major changes in the cloud structure.

A post-flood examination of pictures acquired from ATS-3, NASA's research and development geostationary satellite, showed that a major change in the cloud structure took place during the afternoon and early evening of the 19th. The small, not very bright, cloud lines which had characterized the storm increased in size and brightness until they formed a squall-line formation typical of severe thunderstorm activity. These experimental pictures from ATS-3 are not received by ESSA in real time, because no communications are available to transmit them from NASA's ground station at Rosman, North Carolina, to the National Environmental Satellite Center at Suitland, Maryland.

E. Communications

Meteorological and hydrologic data are collected by a number of different communications systems, including teletypewriter circuits and telephones. The following systems are in use in the Virginia area.

Lynchburg WBO

Meteorological observations are transmitted on the Service A and Service C teletypewriter networks. In addition, hydrologic observations are collected from cooperative observers by telephone, and telephone calls are used to interrogate remote gages. The resulting rainfall and river-gage reports are relayed by telephone to Richmond for further relay to the Washington River Forecast Facility. All Lynchburg responsibilities for collecting rainfall and river data automatically pass to Richmond between 7 p.m. and 6 a.m. when the station is closed.

Richmond Weather Bureau Office

Meteorological observations are transmitted on the Service A and Service C teletypewriter networks. Hydrologic observations collected by telephone from cooperative observers and remote gages, together with those relayed by Lynchburg, are normally sent to the Washington River Forecast Facility by the Radar Report and Warning Coordination (RAWARC) teletypewriter network. When speed is paramount, the reports are relayed by telephone to avoid delays in getting a message on the RAWARC. In addition, general information on storms is collected from a local teletypewriter system with terminals in the Virginia Civil Defense office and in the Virginia State Police office.

Washington Forecast Office

Data are collected from RAWARC, Service A and C, and by telephone. In addition, an Automatic Hydrologic Observing System (AHOS) in the upper Potomac River provides data to the Washington Forecast Office.

There are no indications of failures or troubles with the various teletypewriter networks during the Virginia flood situation. Most telephone capability was interrupted during the night of August 19-20 throughout west-central Virginia. Limited, but delayed, service was available in most areas by midday on August 20. However, in those areas hardest hit by the flooding, service was not restored for several days. Many telemetering gages could not be interrogated as the flood crest moved down the James River flooding out lines and the gages themselves.

F. Findings and Recommendations

Adequate observations are essential to successful forecasts and warnings. In the Virginia flood situation, the surface observing network did not produce a sufficient number of timely reports of the heavy precipitation. The existing radar network could not make up for the deficiency in rainfall reports. When this happens, the forecaster must depend upon a method of forecasting based on physical processes derived from the solution of meteorological equations specifying the trend of atmospheric motions. This method requires observational data concerning the vertical as well as the horizontal extent of the motion system. Its success depends upon the ability of the equations and the observational network to describe adequately the atmospheric motion system. The existing network could not provide the upper-air data needed to accomplish this because its density, at best, gives only an occasional fleeting glimpse of such motion systems.

The task group concluded that:

(1) The rainfall and river-gage substation reporting network failed to provide enough information to describe adequately the rainfall and resulting river stages for use in flood stage and crest forecasts in the middle and lower reaches of the James River Basin. Failures were

due to loss of communications, destruction of gages, and inability of observers to reach the non-telemetering gages because of the storm or high water. In any case, the density of the reporting rain gages was not adequate to have shown the excessive rainfall amounts. A rain gage reporting network of the density required to detect all flash floods is impractical in terms of costs, available sites and cooperative observers, and communications needs.

The communications capability of the ATS-1 satellite has been used successfully, in a test program, to gather the hydrologic data required for operational river and flood forecasting. Funds to begin a program of using the ESSA Geostationary Operational Environmental Satellite (GOES) for automatic relay of rainfall and river-stage reports to collection centers are included in the FY 71 Budget. Properly engineered, such a network could assure that reports would be available in near real time and would continue until the gage was destroyed, giving early warning of catastrophic conditions and data for downstream forecasts.

It is recommended that the present system for collecting and transmitting river and rainfall data, which is largely manual and overly dependent on the human element, be modernized as quickly as possible. To this end, it is recommended that an up-to-date data-collection system, incorporating the latest advances in sensing and communications technology, be developed to assure reliable data, as recommended in "ESSA and Operation Foresight," May 1969.

It is further recommended that the rainfall and river gage reporting system using the GOES relay capability, initiated in the FY 71 Budget, be pursued vigorously, to assure that reliable reports are available in near real time to alert the hydrologic system to heavy rainfall, to furnish key river stage readings, and to serve as "truth" reference points for radar-derived estimates of the areal distribution of rainfall.

(2) The network of regular surface weather-observing stations in southern West Virginia and west-central Virginia is not adequate to detect and describe intense storms the size of Camille in enough detail to accurately assess their motion and intensity. This is especially true at night when several of the stations cease reporting.

It is recommended that, in areas where the regular surface weather-observing network is inadequate to detect and describe intense storms the size of Camille, gaps be filled with a simple, reliable automatic weather station such as the Weather Bureau's AMOS III-70, and that this type of equipment be used to cover periods when regular manned observing stations are not in operation.

It is recommended that WSR-57 radars be installed in the Bristol and South Boston areas and the Washington radar operation moved to Patuxent River, as currently planned, to bring radar coverage in Virginia to a level which will give a high degree of assurance of detecting heavy rainfall and severe local storms.

(3) A major deficiency in weather radar operation lies in the communication of information and data. The semi-plain language code presently used does not adequately convey the large amount of information available in the radar presentations. For many years, the Weather Bureau's Office of Hydrology has supported research to develop techniques for estimating the amount and distribution of rainfall from radar data. The present state of the art permits only limited application of radar data for hydrology. The usefulness of digitized radar data for hydrology has been demonstrated by field testing at the Fort Worth River Forecast Center, where radar and rain-gage data are being compared to develop a means of determining near-real-time area distributions of rainfall as inputs to computerized river-forecasting operations. In the test program, scheduled to end on September 30, 1969, rainfall data acquired by the Oklahoma City radar is digitized, using techniques developed by the National Severe Storms Laboratory, and is transmitted to Fort Worth. This approach offers a solution to the radar data-handling problem and to the fundamental problem of obtaining representative indications of rainfall amounts in river basins.

It is recommended that a prototype radar digitizing system to transmit the large volume of data from radar locations to River Forecast Centers in near real time should be procured and tested for operational suitability to determine if the system and computer programs to relate radar data and "truth" reference rain gages, will meet the needs of the Hydrologic Services System.

(4) The Weather Bureau's radar network can serve as the basis for an effective warning program for flash floods as well as for floods

caused by hurricanes and other intense coastal storms along the Gulf of Mexico and Atlantic coasts and about 300 miles inland. Flash-flood alarms upstream from vulnerable communities, automated rainfall gages around the radars, and constant area surveillance by radar operators would provide immediate warnings, data for longer leadtime forecasts, and an effective means for alerting the Hydrologic Services System.

It is recommended that a flash-flood warning system based on the weather radar network be implemented in 20 States along the Atlantic and Gulf coasts and inland about 300 miles. The system should include:

—automatic rainfall reporting networks, with a minimum of 450 gages, located around 21 existing and planned radars;

—flash-flood warning devices installed upstream from at least 50 communities to provide warnings where other techniques will not suffice.

(5) Cloud pictures from the ATS-3 geostationary satellite would have been useful to meteorological personnel in detecting the changing cloud structure of Camille on the afternoon of August 19, and might have served as an indicator of intensification taking place.

It is recommended that arrangements be made to obtain from NASA's geostationary satellite ATS-3 cloud pictures in real time at the National Environmental Satellite Center and to initiate real-time watch and interpretation of these pictures for storms such as Camille.

Chapter IV

Forecasts and Warnings

A. Meteorological Forecasts

Advisory Number 20 on Hurricane Camille was issued at 11 a.m. CDT, Monday, August 18, 1969, by the Weather Bureau Hurricane Warning Office at New Orleans. The hurricane's center was located at that time about 50 miles north of Jackson, Mississippi, and was moving northward at 18 mph. Maximum winds of 50 mph were forecast to decrease as the weakening hurricane moved northward, with up to 5 inches of rain expected through northern Mississippi, western Tennessee, and western Kentucky. This was to be the last advisory; but Kansas City would issue a bulletin at 2 p.m. CDT, if needed.

Kansas City issued a 2 p.m. bulletin, stating that the center of the rapidly weakening remnants of Camille was located near Greenwood, Mississippi, and was moving northward at 17 mph. Maximum winds had decreased to 45 mph and were forecast to diminish further during the evening. With the storm's passing, rains up to 4 inches were expected to continue to spread northward into western Tennessee, western Kentucky, eastern Arkansas, and southeastern Missouri. No further bulletins were planned, but statements concerning rainfall and floods would be issued by Weather Bureau Offices in areas noted.

The Weather Bureau Office at Memphis issued statements at 1 p.m., 3 p.m., 4:30 p.m., 6 p.m., 7 p.m., and 9:15 p.m., August 18, noting the movements of the weakening storm from near Greenwood to Memphis. Maximum winds had decreased to 30-40 mph, and the rainshield had spread northward to southern Illinois, western Kentucky, and middle and southeastern Tennessee. The 9:15 p.m. statement terminated Memphis' actions on Camille.

A brief statement was issued by the Weather Bureau Office at Cairo, Illinois, at noon, August 18, 1969, calling for heavy rains to spread northward with the remnants of Camille. Flash flooding was expected in southeastern Missouri, western Kentucky, and southern Illinois for the next two days.

The Weather Bureau Office at Louisville, Kentucky, issued statements at 10:30 a.m., 3 p.m., 6:30 p.m., and 10:30 p.m., August 18, and 7:45 a.m., 8:45 a.m., and 2:45 p.m., August 19, to follow the remnants of Camille from northern Mississippi through western Tennessee to central Kentucky with expected eastward movement to eastern Kentucky by evening. Heavy rains up to 2-3 inches, were forecast for central and western Kentucky, tapering to an inch or slightly more in eastern Kentucky during the evening. The 2:45 p.m. statement gave a resume of rainfall amounts—varying from a trace to nearly 3 inches with the storm. The statement also noted an absence of flooding due to the steady character of the rain, a preceding dry week, and heavy vegetation.

Routine area and State forecasts were issued by the Washington Forecast Center at 4 p.m. and 9:30 p.m. on the 19th, moving the low pressure center and moderate rainfall across West Virginia into northern Virginia by the morning of the 20th. These forecasts followed the guidance provided by the National Meteorological Center. Similar forecasts were issued by Richmond and Lynchburg.

At 11:45 p.m. EDT on the 19th, police at Buena Vista, Virginia, advised the Richmond Weather Bureau Office that the river stage was 11.8 feet and rising; no report of rainfall amount was available. The meteorological technician on duty at Richmond telephoned the Principal Assistant at his home and informed him of the report. He was told that rains were expected in the area and to treat it as local flash flooding. The meteorological technician coming on duty at midnight was aware of the call. No professional meteorologist is regularly on duty during the night because of limited staffing. At 01:46 a.m. EDT, the State Police reported over the local teleprinter circuit that heavy rains in

Louisa County (central Virginia) were causing considerable flooding of highways. The cooperative observer at Clifton Forge reported by telephone at 2:00 a.m. EDT that 8.44 inches of rain had fallen in the last 24 hours with 5.5 inches of this in the last 5 hours; James River stage at Lick Run at 2 a.m. was 11.99 feet.

The rainfall report from Clifton Forge was sent to Chicago via RAWARC at 2:30 a.m. EDT as a newsworthy item for inclusion in the National Weather Summary prepared there. The message also included information that State Police had reported flooding in Nelson, Fluvanna, Albemarle, Amherst, and Louisa counties.

The duty forecaster at the Washington Area Forecast Center monitored the Automatic Hydrologic Observation System (AHOS) readouts of rainfall and river stages in the Shenandoah/Potomac River Basin about 2:30 a.m. He noted that 3 inches of rain had been reported at Stuarts Draft, Virginia. With some doubts as to the validity of the report because of previous malfunctions of AHOS, he called the report to the attention of the NMC Quantitative Precipitation Forecast section. Following receipt of the Clifton Forge report (called to his attention about 3 a.m. by an alert assistant who saw the report on RAWARC), the duty forecaster called Richmond to discuss the situation. It was agreed that Washington would issue a statement as soon as possible, and that Richmond would follow with one for Virginia using the Washington guidance.

The Washington Forecast Office issued its statement at 3:39 a.m. EDT, August 20, 1969, regarding the heavy rains and flooding reported in west and central Virginia and southern West Virginia. The remains of Camille were now located in southwestern Virginia and were moving eastward at 20-25 mph. Rains of 8-9 inches had been reported along with flooding in many counties; rainfall in excess of 2 inches was forecast to spread eastward over central Virginia, causing flooding of small streams and low areas. The Richmond Weather Bureau Office followed the Washington statement at 4:00 a.m. EDT, August 20, adhering to the guidance provided. The information was essentially repeated at 6:45 a.m. EDT in the regularly issued Virginia Weather Summary. Both the 4 a.m. and 6:45 a.m. issuances were relayed on the Richmond local teletypewriter loop and RAWARC.

B. River and Flood

River and flood forecasting operations began about 5:30 a.m. EDT on the 20th when the hydrologic specialist at the Washington River District Office reported for work some two hours early due to his concern about possible flooding in the Potomac Basin. After quickly surveying the few rainfall and river stage reports available and checking the latest reports from his automated reporting system in the Shenandoah/Potomac Basin, he alerted the duty hydrologist at the Washington River Forecast Facility not long after 5:30 a.m. EDT.

Actual work on flood forecasts for the James River Basin began nearly simultaneously around 7 a.m. on the 20th at Lynchburg, Richmond, and the Washington River Forecast Facility.

At Lynchburg, the Meteorologist in Charge opened the station for the day at 6:00 a.m. EDT. At about this time, the cooperative observer at Kerrs Creek, Virginia, called Lynchburg an hour early because his rainfall was 6-8 inches, the river was high and rising rapidly, and things looked bad. He regretted not having called in during the night, but his wife wouldn't let him go out in the storm to the gages (Mr. Kenneth M. Chittum is 81 years old and a long-time cooperative observer). The Meteorologist in Charge immediately began calling his local river warning list with information that the river was high and would rise rapidly; no specific stages were forecast but the alert was out. The next two to three hours were devoted to collecting and attempting to collect rainfall and river-stage reports for telephone relay to the Richmond River District Office. The problems in this respect have been discussed under Observations and are not repeated here. There was considerable pressure for specific crest forecasts for the upper James River, and at 11:25 a.m. EDT, a call was placed to the Director, Eastern Region, advising him that a disastrous flood was in progress and that specific forecasts were urgently required from the River Forecast Facility. The requested forecasts were received by telephone relay from Richmond River District Office in about an hour after this call. The forecast called for the James to crest at Lynchburg at 28-30 feet early on August 21; the river crested at 28 feet early in the afternoon of the 20th.

Flood forecast operations at the Richmond River District Office began shortly after 7 a.m.

EDT, when the Principal Assistant arrived early in response to a telephone call from the meteorological technican on duty. He began collecting rainfall and river stage reports. The Meteorologist in Charge arrived at 8:30 a.m. EDT, and began assessing the situation and coordinating with the River Forecast Facility in Washington. By midmorning, the seriousness of the situation was beginning to become evident, and a public statement was issued at 11 a.m. EDT, August 20, stating that severe flash-flooding had taken place in the upper James River Basin, that flood stage would be reached all along the James to Richmond by evening, and that detailed crest forecasts would be available early in the afternoon.

A detailed river-forecast bulletin, confirming telephoned warnings, was issued at 3 p.m. EDT, based on forecasts received via telephone from the River Forecast Facility about noon on August 20. The bulletin noted that the most severe flood since 1936 was in progress. Forecast crests, along with flood stages, actual crests, and previous records are given in Table II.

TABLE II

JAMES RIVER CREST INFORMATION

Location	Flood Stage	Crest Forecasts Issued on Local Loop by Richmond RDO				Actual Crest	Record Crest
		3 p.m. Aug. 20	12:15 p.m. Aug. 21	4:15 p.m. Aug. 21	12:10 a.m. Aug. 22		
Lick Run	10	Crested				25.5 ft. Aug. 20	33 ft. 1877
Buchanan	17	26-27 ft. Aug. 21			Falling	23.4 ft. Aug. 20	34.9 ft. 1877
Buena Vista	17	Crested				**30.5 ft.** Aug. 20	22 ft. 1936
Lynchburg	18	29-30 ft. Midnight				28.0 ft. Aug. 20	30 ft. 1771
Scottsville	20	30 ft. Aug. 20 & 21			2nd Crest 24-25 ft. then fall	**31.5 ft.** Aug. 20	30.7 ft. 1870
Bremo Bluff	19	32-33 ft. Aug. 20 & 21			2nd Crest 32-33 ft. Aug. 22	**39.1 ft.** Aug. 20	30.5 ft. 1870
Palmyra	15	Crested				**39.85 ft.** Aug. 20	37.4 ft. 1942
Cartersville	20	29 ft. Aug. 21				**33.8 ft.** Aug. 21	30.4 ft. 1877
Columbia	18	36-37 ft. Midnight			Falling	**41.3 ft.** Aug. 20	39.0 ft. 1870
State Farm	12	25 ft. Aug. 21					26.4 ft. 1944
Richmond Westham	12	22 ft.* Aug. 21	28-29 ft. Aug. 21	28 ft. Midnight	25 ft. By 1 a.m.	**24.8 ft.** Aug. 21	23.4 ft. 1936
City Locks	9	24-25 ft.** Aug. 21	34-36 ft. Aug. 21	34 ft. Midnight	30 ft. By 2 a.m.	28.64 ft. Aug. 22	30 ft. 1771

* Revised to 26 ft. at 4:30 p.m. EDT, August 20, 1969.
Revised to 26-28 ft. at 7 p.m. EDT, August 20, 1969.
**Revised to 32-34 ft. at 7 p.m. EDT, August 20, 1969.

Boldface values in the Actual Crest listings indicate a new all-time record.

Subsequent forecasts made little or no change in crests above Richmond. However, the crest forecasts at the two Richmond gages, Westham and City Locks, were revised upward twice from the afternoon of August 20 until the afternoon of August 21. The revisions, incorporated in Table II, changed the Westham crest from 22 feet to 28-29 feet, then to 28, and finally to 25 feet. The City Locks crest was changed from 24-25 feet to 34-36 feet, then to 34 feet, and finally to 30 feet.

The Richmond River District Office generally followed the forecasts furnished by the River Forecast Facility. The River Forecast Facility forecasts were as follows:

Issued Noon, August 20, 1969
Lick Run: Crest 25-27 feet on 21st.
Buchanan: Crest 25-27 feet on 21st.
Buena Vista: Above flood through midnight.
Holcombs Rock: 30-32 feet at midnight.
Scottsville: 25 feet on 21st and 22nd.
Palmyra: At flood now.
Richmond/Westham. At flood by 4 p.m.

Issued 2 p.m. August 20, 1969
Richmond/Westham: Tentative 22 ft. for limited distribution.

Issued 4 p.m. August 20, 1969
Cartersville: 31-33 ft. on 21st.
Richmond/Westham: 26-28 ft. on 21st.

Issued 9:15 a.m. August 21, 1969
Richmond/Westham: 28.5-29 ft. on 21st.
Richmond/City Locks: 37-38 ft. on 21st.

Issued 3:30 p.m., August 21, 1969
Buchanan: Below flood afternoon.
Holcombs Rock: Below flood afternoon.
Scottsville: Second crest 24-25 ft. on 22nd. Below flood afternoon 22nd.
Richmond/Westham: 28 ft. before midnight (issued at 4 p.m.)

Richmond/City Locks: Stay with low end of bracket issued by RDO (34-36 ft.). Crest about midnight.

Issued 2:15 p.m. August 22, 1969
Recession forecasts

The Washington River Forecast Facility, like all river forecast centers, operates on a daytime basis Monday through Friday and depends on the meteorological system to alert it when needed. In this case, the River Forecast Facility was alerted by the Washington River District Office shortly after 5:30 a.m. EDT, August 20. Work began on collecting data and preparing the forecasts for the James River Basin at 7 a.m. Forecasts were made according to accepted procedures, and the only criticism voiced was aimed at the delay in issuing the first set of specific crest forecasts. The difficulties in obtaining adequate, representative, and reliable data from the rainfall and river gages in the area have been discussed and were the principal reason for the delay. There was no evidence of excessive delays in the River Forecast Facility once data became available. Normal 8:30 a.m.- 5:00 p.m. working hours were expanded to meet the needs of the situation; river forecast personnel were on duty most of the night and were on call during the remainder if conditions changed.

The errors in crest forecasts at Richmond require explanation, at least in terms of the problems faced by the River Forecast Facility and River District Office. The major source of error in the forecasts was the nearly total breakdown of the rainfall and river-stage reporting network when it was needed the most. As a result, the River Forecast Facility and River District Office just didn't know how much water they had and what its precise distribution was in the basin. At no time during the flood were enough reports available to define the actual rainfall pattern. A second major source of error was the fact that record crests were reached at many gages, and discharge ratings, which relate stage height to stream flow, had to be extrapolated far above the record of maximum stage/flow. Where the extrapolation was in error, the forecast system was dealing with too much or too little water, and downstream forecasts were correspondingly in error. This problem always exists with record flooding. Finally, it appears that this flood, which began as a flash flood, continued to have many flash-flood characteristics. For example, the water crested and fell rapidly all the way downstream to the estuary, with corresponding difficulties in forecasting actual crest heights.

C. **Dissemination**

Since there was no warning of the heavy rains and resulting flash flooding in the upper reaches of the James River, the adequacy of warning dissemination facilities could not be evaluated in those areas. In the middle and lower reaches of the James River where significant warning leadtimes were provided, it was possible to assess the adequacy and effectiveness of the dissemination system.

The only ESSA facility that played a significant role in this situation was the RAWARC teletypewriter network, which served as a means for Washington and Richmond offices to keep one another advised of events and forecasts. RAWARC is not normally used to transmit River Forecast Facility crest forecasts to RDO's; telephone is used so that the forecasts can be discussed in private before they are committed to wide distribution. Also, river and rainfall reports often are relayed via telephone to avoid the delays and manpower required to wait for a break in this usually busy network.

There is no ESSA Weather Wire Service in Virginia, and there is some question as to how useful it would be in rural areas where the small radio stations and newspapers probably would not be able to afford the costs involved. These small stations and newspapers get their information over news service teletypewriters and telephone calls from the Weather Bureau, Civil Defense, police, etc.

The principal means of disseminating information in the Lynchburg area of responsibility is personal telephone contacts—19 calls are required to alert river interests in the area to flood conditions. This includes local officials, police, and various mass media.

In Richmond, the principal means of disseminating information locally and Statewide is the local teletypewriter loop connecting the Weather Bureau with mass media, city officials, State Civil Defense Headquarters, and Headquarters of the Virginia State Police. Civil Defense and the Virginia State Police have Statewide teletypewriter systems, which are used to relay warnings to all counties (Civil Defense and/or sheriff) and to Virginia State Police offices. These offices are responsible for further relays to local officials and mass media. While there was no means of determining how well the system would operate under a short-fuse warning, it does appear possible to get a warning to the larger cities and towns with good speed and reliability; radio is available to back up the teletypewriter systems. From this point, even the local radio stations have limited capability to reach many of the isolated communities in the mountainous areas of the state. Most notifications of flash flooding were by police and volunteers, since power and telephone lines failed rapidly as the flooding developed.

Responsible local and state officials were asked: "Would a short leadtime warning of the heavy rains and flash flooding have been effective?" Their answers are summarized here.

Mr. J. M. Batchelor, Jr., County Executive of Albemarle County: There is no way to get the word to people in rural areas at night. Radio coverage is limited and use of police cars was restricted early by flooding in low-lying areas. He also noted that he was a native of Florida where the people have learned to respond to the Weather Bureau's warnings; he doubted that there would have been much response by many people. The Sheriff of Albermarle County reflected similar views.

Major General A. B. Denniston, USA (Ret.), Director of Civil Defense in Virginia: He observed that there were two problems associated with warnings of natural hazards. First, there is the matter of getting a warning issued, distributed to officials, and disseminated to the people. Second, there is the matter of credibility of the warning and the willingness of people to believe it and react. A warning could have been distributed to county and city officials but, because of the time of night and rural character of much of the area involved, there is serious doubt that many people would have responded to a reasonable warning of heavy rains and local flooding since it happens not infrequently. There is doubt that people would have believed a warning calling for the catastrophic events in the counties where rainfall was heaviest.

Colonel H. W. Burgess, Superintendent, Virginia State Police: He essentially reaffirmed the views expressed by General Denniston. A warning could be distributed to officials but from there on it is difficult to get to people, especially at night. Also, some people did not respond to the alerts by police.

Captain Benjamin Miller, Richmond Port Captain (and the City of Richmond focal point for flood actions): The flood emergency plan was put in effect just before noon on August 20, 1969 on his initiative. When the Weather Bureau forecast of 32-34 ft. at City Locks came out he was shocked since this would flood the city disastrously, but preparations were started to prepare for this crest the following day. While the forecast crest was substantially too high, no officials are unhappy over not having a major disaster. He stated that he and the city felt that the service was outstanding in view of the nature of the flood.

D. Findings and Recommendations

Two distinct problems were encountered in the warning process. The first of these was meteorological. Prediction of heavy rains, and of their amount and duration, is vital to warnings of flash floods in any river basin. Once the rain has fallen and its distribution over the watershed has been ascertained—or, alternatively, the amount of water carried by the streams becomes known—the problem is a hydrologic one. In the Virginia flood situation, the meteorological problem was not solved adequately. The hydrologic problem of forecasting flood stages and crests was solved as well as the available data would allow.

The task group found that:

(1) No forecasts or warnings of heavy rainfall or flooding were issued for the James River Basin by the Weather Bureau prior to 3:39 a.m. EDT on the 20th, when the Washington Forecast Office issued its statement noting the events that had occurred during the night. Forecasts issued followed the guidance provided by the National Meteorological Center, which indicated a northeastward rather than an eastward movement of the low pressure center and rainfall area as shown in Figure 9.

The 24-hour predicted position given by NMC was near Washington, D. C., whereas the remains of Camille were actually observed near Richmond, Virginia. This is a prediction error of about 100 miles in 24 hours for the position of the pressure system, which in itself is quite acceptable for the prediction of larger scale motion. Accurately predicting the movement, as well as the intensification and the related weather, of a storm such as Camille is extremely difficult within the current state of meteorological science. An assessment of the upper wind flow into and out of the pressure system's center and its changes with time is vital to a successful forecast.

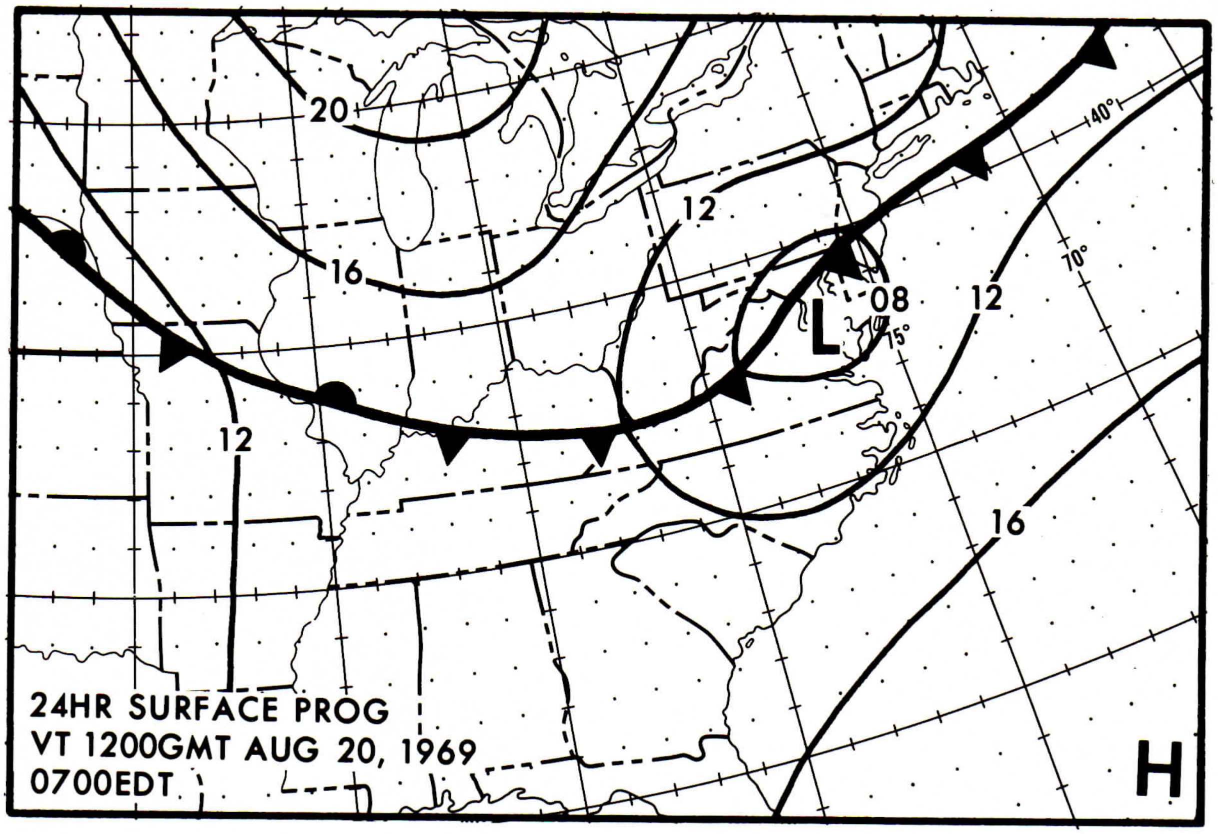
Lacking the needed observations upon which to base a correct prediction of these wind motions, the operational Quantitative Precipitation Forecasts (QPF) produced at the NMC were of little benefit to forecasters in relation to precise location of the rainfall in Virginia or prediction of the incredible amounts of rain that fell there. Precipitation associated with Camille occurred in the United States on three days. These days were the 24-hour periods ending at 1200 GMT on August 18, 19, and 20. Of these three days, only one turned out to be critical in connection with the effects of Camille—August 20. The heavy rains that resulted in the devastating floods in the James River Basin of Virginia fell during the evening of the 19th and early morning of the 20th. The other two days can be eliminated from the discussion, because on August 18 the storm surge from the Gulf of Mexico was by far the major factor in the disaster, and on August 19, rains sufficient to cause loss of life or significant property damage did not occur until very late in the evening.

Error in the forecast movement of the storm resulted in the axis of maximum precipitation being predicted also somewhat too far to the north. This can be seen in Figures 10 and 11, which show the 12-hour and 24-hour QPF verifying at 1200 GMT August 20, along with the observed rainfall. It should be noted that the very heavy rainfall which later reports disclosed was not reflected in the "Observed Precipitation" charts.

In summary:

> The *maximum* amount of precipitation forecast over southwestern Virginia during the 24-hour period ending at 1200 GMT August 20, was little more than an inch. The maximum amount of precipitation reported in southwestern Virginia by verifying time was 8.44 inches, and subsequent reports show a maximum of 27-28 inches.
>
> The area of actual heavy precipitation reported over Virginia is smaller than the average spacing between upper-air sounding stations; consequently it is lost in the numerical computation process.
>
> Objective and subjective forecasting techniques in use are not capable of predicting record or near-record events.

A fundamental problem facing the forecaster is the adequacy of weather-observing networks. Not only must the atmosphere be observed over broad areas for analysis and prediction of the large-scale atmospheric circulations, but it must also be sampled in sufficient detail to permit



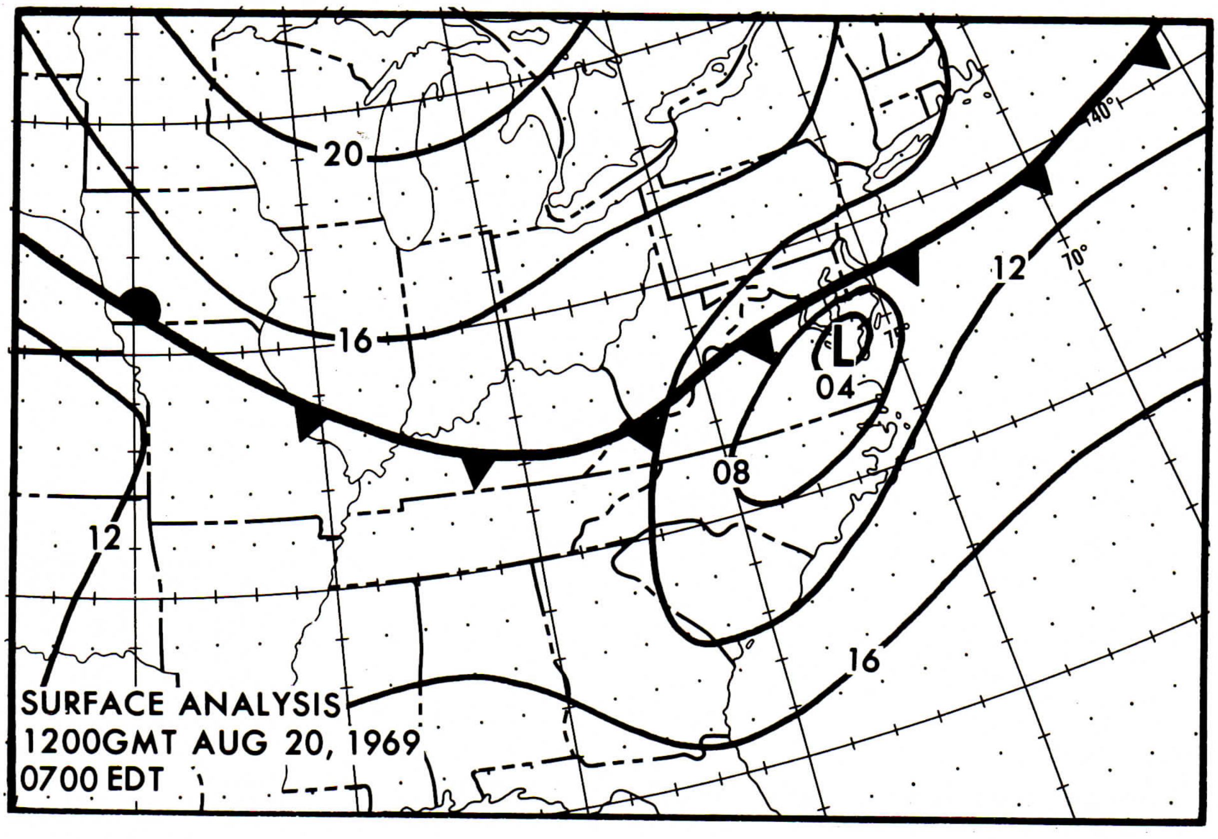


Fig. 9—Forecast and Observed Surface Weather Charts 1200 GMT, August 20, 1969

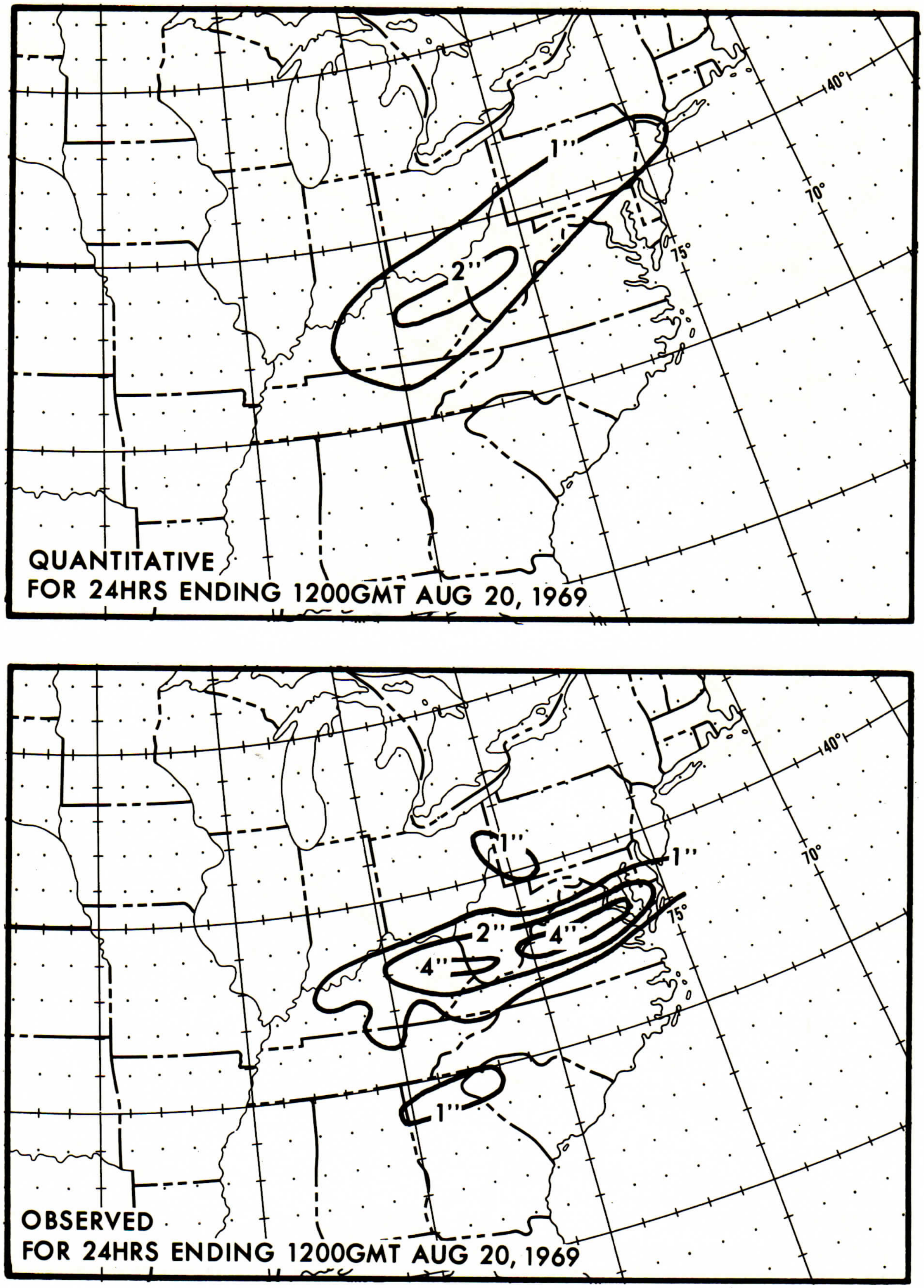


Fig. 10—Forecast and Observed Precipitation for 24 Hours Ending 1200 GMT, August 20, 1969

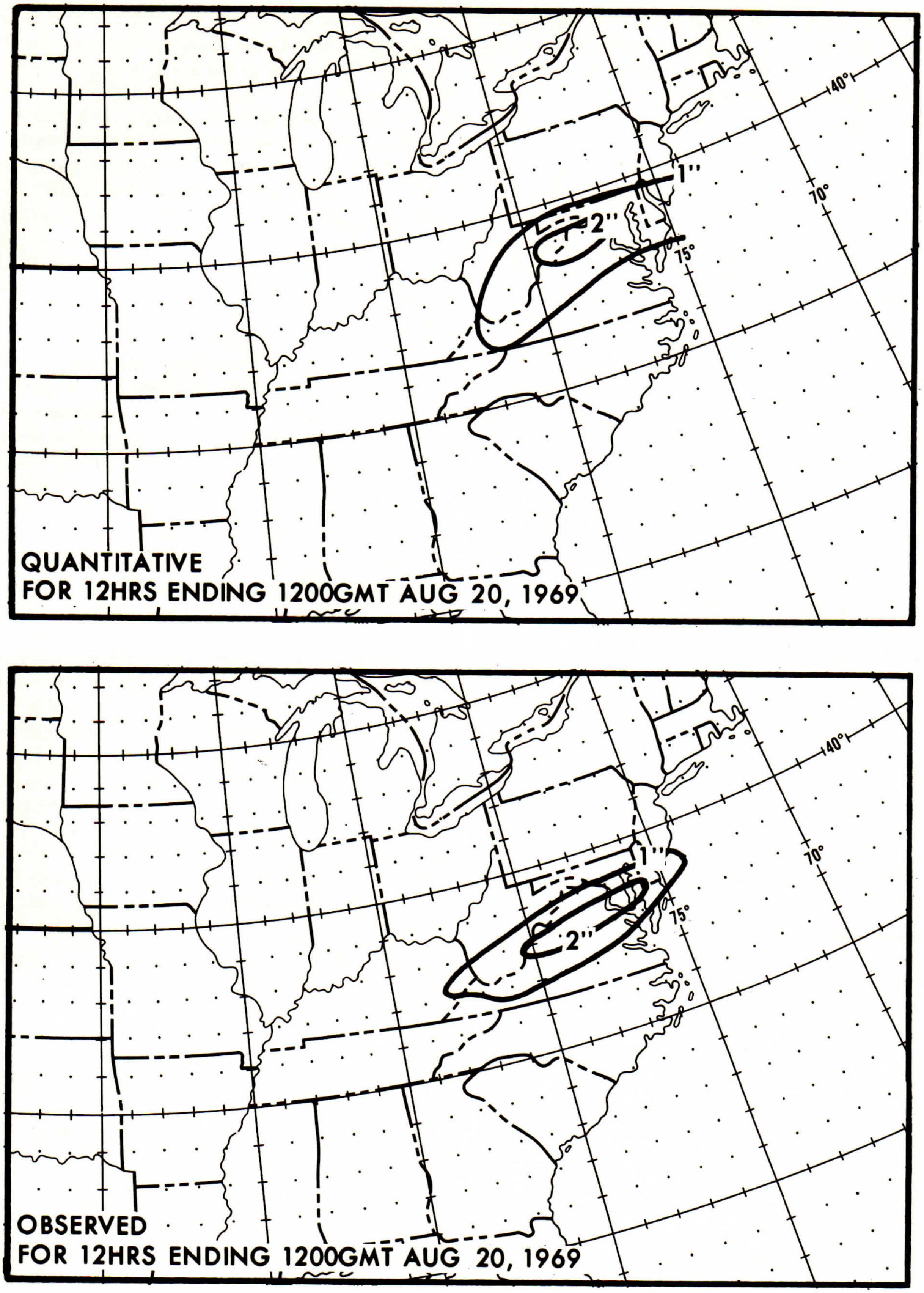


Fig. 11—Forecast and Observed Precipitation for 12 Hours Ending 1200 GMT, August 20, 1969

the prediction of weather associated with small-scale atmospheric motions. Small-scale atmospheric motions may be arbitrarily defined as those whose characteristic horizontal dimensions are on the order of a few tens of miles. Weather typical of such systems includes heavy snows, in which accumulation may exceed one inch per hour, and thunderstorms that produce hail, damaging winds, and tornadoes. During the past two decades, increasing attention has been given to describing, understanding, and predicting these phenomena. The principal emphasis has been directed toward the subjective assistance provided by weather surveillance radar, and toward the development of empirical and objective techniques relating small-scale motions to the much larger-scale motion systems. In the case of empirical and objective techniques, the few that exist for the prediction of heavy precipitation were completely inadequate in the Virginia storm, because they are based on statistical averages and empirical relationships and cannot consider the consequences of anomalous conditions. This is partly due to the paucity of upper-air observations. Further significant progress requires increased density of measurements in order to define the atmospheric processes involved in the development and propagation of small-scale systems.

Marked improvement in forecast proficiency for small-scale storms is not anticipated until more is known about the three-dimensional structure of small-scale systems. This will lead to the design and implementation of the observational network, and will permit the design of the communication and processing portions of the warning system. Its costs can then be weighed against the economic and social benefits that might be realized.

It is recommended that action be taken to improve knowledge of the genesis, growth, and dissipation of small-scale systems, leading to better description, understanding, and prediction of related weather phenomena.

It is further recommended that the increased knowledge then be applied to the improvement of observation, processing, and prediction subsystems, and that ESSA establish as its goal the redefinition of these subsystems by 1975.

(2) Once the Hydrologic Service System was activated, the river and flood forecasts issued by the Washington River Forecast Facility, the Richmond River District Office, and the Lynchburg Weather Bureau Office were as timely and accurate as the data-acquisition system would support. There was a series of reports, beginning shortly before midnight on the 19th and continuing into the early hours of the 20th, which could have alerted the Richmond Weather Bureau Office that events were not going as forecast in west-central Virginia and that the meteorological as well as hydrologic system should be called into full operation. This would have done little if anything for the flash-flood area, but the downstream warnings would have had more leadtime.

It is recommended that instructions in the Weather Bureau Operations Manual be reviewed to assure that: (a) reports of potentially hazardous conditions received from cooperative observers or other reporting sources are promptly brought to the attention of a responsible professional-level employee in those offices where 24-hour coverage by professionals is not possible; and that (b) reports of this type are relayed promptly and directly, by the fastest means available, to the responsible forecast office.

(3) The somewhat anomalous organizational location of the Washington River Forecast Facility as a part of the research and development structure in the Weather Bureau's Office of Hydrology had no bearing on the timeliness or accuracy of the forecasts issued. It does, however, deprive the Director, Weather Bureau Eastern Region, of operational and administrative control of a unit vital to his service responsibilities.

It is recommended that the Washington River Forecast Facility be placed under the administrative and operational control of the Director, Weather Bureau Eastern Region, as soon as possible. Plans for consolidating the Washington, D.C., and Harrisburg, Pennsylvania, centers reflected in the FY 71 Budget should be continued, but correction of the organizational anomaly should not be contingent on the FY 71 Budget action.

(4) The bulletins and statements issued by Kansas City, Memphis, Cairo, and Louisville through the afternoon of August 19, 1969, followed the NMC guidance and adequately predicted the movement, rainfall, and flash flooding associated with the remnants of Camille in their areas of responsibility. Discontinuance of formal bulletins on the storm during the after-

noon of August 18 was a coordinated action between the National Severe Storms Forecast Center in Kansas City and the Weather Bureau's Emergency Warnings Section. Weather Bureau Operations Manual, Part C, Chapter 41 requires continuation of bulletins so long as a storm poses a threat to life and property. While there is no firm basis to conclude that continuing the bulletins would have in any way led to forecasts or warnings of events on the 19th and 20th, their continuance would have assured more attention to the storm.

It is recommended that Weather Bureau Operations Manual, Part C, Chapter 41 be revised to require that Warning Coordination Centers continue to issue bulletins on a tropical cyclone so long as it or its remnants constitute a recognizable low-pressure center or rainfall area within the United States and its coastal waters.

(5) The methods for distributing warnings of natural disasters in Virginia are typical of that in most states. The excellent police and Civil Defense networks will get the word to responsible officials in the cities and larger towns. From this point onward, no reliable method exists for alerting people in smaller communities and rural areas, especially at night when radio stations are off the air and the people are asleep. Heroic efforts by police and volunteers saved countless lives in Virginia, but they were unable to reach a large number of people before the rising waters cut off roads and telephones.

Where an organized community-action program for flash-flood warning had been established, there was some warning and necessary evacuations were successfully completed. A similar situation existed where the arrangements were informal, but a responsible official armed with information took action. Local arrangements such as these offer the only real hope for distributing flash-flood warnings.

It is recommended that ESSA in cooperation with the Office of Emergency Preparedness and State officials, attempt to strengthen the community-action flash-flood program, providing sufficient staffing in Weather Bureau offices to develop and establish the local warning systems.

It is further recommended that a flash-flood alarm system—in which a detector located upstream from the community causes an alarm to sound in the police station or other location when the stream reaches a danger level—should be incorporated in the community-action program. The system is estimated to cost $2,500 installed.

It is also recommended that ESSA consider a joint effort with NASA to investigate the feasibility of a natural disaster direct broadcast satellite to relay warnings to the wide segment of the population not now reached directly by the warning communications system.

(6) Considerable effort has been devoted to the development of conceptual hydrologic models for the continuous simulation of streamflow. Several models now being tested and refined should ultimately result in an operational procedure that will make more use of computer capabilities and make possible more timely and accurate river forecasts.

It is recommended that research and development activities aimed at more timely and accurate river forecasts be continued. Emphasis should be given to developing hydrologic models and related computer programs which will continuously simulate streamflow from rainfall and river-stage reports.

DEPARTMENT OF COMMERCE
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