NOAA Technical Memorandum NWS WR-82

FLASH FLOOD FORECASTING AND WARNING PROGRAM IN THE WESTERN REGION

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First printed December 1972
Revised March 1978

UNITED STATES DEPARTMENT OF COMMERCE
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I. INTRODUCTION

A flash flood is distinguished from a river flood by a very rapid rise in runoff water, and is usually defined as a damaging flood occurring within four hours of the causative event. Flash floods in western United States are usually associated with heavy thundershowers, most of which have their origin in the mountains, so that flooding frequently occurs less than an hour after the downpour. The area affected is very limited, usually confined to a single stream or drainage. Since the heaviest rainfall frequently occurs in inaccessible wilderness country, instrumentation and human witnesses are often lacking, so flooding may take place with little or no warning. Extensive flash floods often result from a hurricane that has moved inland and turned into an extra-tropical storm in eastern United States, but this type of situation is relatively infrequent in the West. However, tropical moisture, associated with a hurricane off the coast of Mexico which has been moved northward by the general circulation, is a common cause of heavy showers and flash flooding in the southwestern states [1].

Rate of fall and area covered by the shower are determining factors in flash floods. As little as an inch of rain concentrated in a small drainage basin within an hour can produce flash flooding. Even antecedent condition of the soil is of minor importance when rate of fall is excessive. In steep canyons or valleys, whether the soil is wet or dry, most of the rain will run off if it falls rapidly enough.

Limited flash flooding can occur almost anywhere that thundershowers occur. Almost any locality could be hit by a freak thunderstorm that would drop rain much faster than drainage channels could handle. However, in many places, a thunderstorm of this intensity would be so unlikely that it would be unreasonable to go to extraordinary means to protect against it.

In order to develop a realistic flash-flood warning program, it is necessary to have some idea of the incidence in various areas in order to distribute resources efficiently. In the Western Region, Arizona, southern Nevada, southern Utah, and southeastern California have presented the greatest flash-flood problems in recent years. During the summer monsoon, tropical air moves into this area from a southerly direction and produces numerous heavy thundershowers. A significant

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factor is the general rise in terrain. In Arizona, this rise is from less than 1,000 feet above sea level in the Salt River Valley in southern Arizona to 7,000 feet (and peaks to 12,000 feet) on the Mogollon Rim less than 100 miles away. Flash floods in Arizona are mostly associated with runoff in the various valleys of the Rim and associated mountains. In August of 1971, 28 days had flash flooding some place in Arizona.

A different type of flash-flood situation exists in the winter in California. Under certain conditions, very moist air moves in from the Pacific and is forced to rise over the mountains resulting in copious rains for days at a time. These rains produce runoff which is very "flashy" because of the steep terrain and short runoff channels, so flash floods do occur, along with more generalized flooding due to heavy, continuous rain. A notable case of this type occurred in January and February 1969 when fifty-three people were killed and thousands of homes were destroyed by flood and mud slides in southern California with damage of 268 million dollars. Of great importance in this and other such floods is the increased runoff resulting from denuded slopes that have been burned previously in extensive fires. Also, the construction of homes and other man-made development has decreased the natural moisture retention capability of the soil. This type of flash flooding, which is really an adjunct of more generalized flooding, is a special problem in itself and will not be treated in this paper.

At a much lower level of incidence, flash flooding also occurs in and near the mountains of all other parts of the Western Region. It is difficult to identify just where the danger is greatest since records of flash floods have not been kept until recently. Furthermore, a sparse population in mountain areas does not permit reporting of all flash floods. Only recently, with burgeoning of recreational activities in the mountains, has the problem of flash flooding become prominent. It is of interest to note that the most disastrous flash flood of record in this region occurred at Hepner, Oregon, in June 1903 and claimed over 200 lives. Most flash floods in the West are capable of claiming lives and doing damage to property and streambeds. The Labor Day storm of September 1970 in northern Arizona produced flash floods which killed 23 people and did property damage of over 5 million dollars.

II. REQUIREMENTS FOR EFFECTIVE WARNING

Warning of flash floods is largely an observational problem. Potential for occurrence of heavy rains can be forecast by synoptic means and used as a basis for a Flash Flood Watch, but specific areas where excessive rains will fall cannot be realistically predicted in most cases and must be determined using radar, satellite data, and reports by witnesses. Program emphasis must be placed upon areas in which people and removable property can be protected by such service.

A. Radar. Because of the sparse population in areas where flash floods have their genesis, radar is the best potential tool for predicting these floods once the system develops. However, this tool is greatly handicapped in the West since the mountains interfere greatly with radar transmission. The use of radar in forecasting flash floods is discussed in Section IV of this paper.

B. Spotter Networks. In areas with considerable potential for flash floods, spotter networks can be very helpful. Because of the erratic nature of flash flooding, such a network must ideally be very extensive in order to cover a reasonable fraction of the important watersheds. Data Acquisition Division of Western Region Headquarters (WRH) is providing a computer printout of locations and phone numbers of all substation observers in the Western Region. Cooperation of these observers should be enlisted wherever possible. In Arizona, for example, an extensive spotter network has been set up with minimum effort by enlisting services of these observers. A letter was sent to each of the approximately 300 climatological observers in the state asking permission for Phoenix Weather Service Forecast Office (WSFO) to call for information in storm situations, and also inviting the observer to call Phoenix WSFO collect under certain conditions of weather of special interest. Most observers agreed to cooperate. Calls to any individual observer are infrequent and the program has proved very effective in determining where the problem areas lie in a given storm. It would be difficult to set up such an extensive network in any other way without great expenditure of time and money. This program should be coordinated with the Network Manager.

The most frequently used type of network involves the cooperation of state highway patrol, state highway maintenance crews, sheriffs' offices, fire departments, and other public employees. This type of reporting network is used by most weather offices, and is particularly effective because reporting officials are also the action officials if an emergency develops.

C. Flash Flood Alarm Gages. Use of alarm gages can be very effective in certain types of watershed, and there are many places in the Western Region which could use these gages to advantage. This equipment is set to trigger an alarm in an office with 24-hour duty, personnel of which will take protective action when water reaches a predetermined height. The most practical use for these installations is generally above towns or other valuable installations that require protection.

III. PREPAREDNESS PROGRAMS

The National Weather Service (NWS) has a well-organized program for issuing watches and warnings and distributing them through the public dissemination media. In brief, this program consists of three types of issuances--Alerts, Watches, and Warnings. The Flash Flood Alert is an internal issuance, put out by the WSFO to advise the Weather Service Offices (WSOs), River Forecast Centers (RFCs), and River District Offices (RDOs) of the danger that flash flooding will develop, based on rainfall forecasts. When the situation crystallizes enough to justify alerting the public, a Flash Flood Watch is issued by the WSFO covering the area over which flash floods are expected to develop. When specific areas in real danger of flash flooding can be identified, Flash Flood Warnings are issued, primarily by the office with County Warning Responsibility.

In some communities still further preparation is needed to deal with flash floods, since they are such "short-fuse" events and action must be taken with very little notice. A community preparedness plan is developed and a committee is set up to carry out this plan. When a flash flood threatens or a Flash Flood Watch is issued by the NWS, the committee swings into action to carry out the plan. This will include gathering local reports on rainfall and stream levels and computation of stream rise, using procedures that have been developed specifically for that community by the National Weather Service. As the danger develops, the committee will keep the public informed and will arrange evacuation or other protective measures as needed. An on-site operation such as this is able to save precious minutes in the critical stages of flash flooding. Careful planning and preparation, with the cooperation of the NWS, provide the expertise needed.

IV. FORECASTING OF FLASH FLOODS

A. Procedures.

1. <u>Climatology</u>. The first step to be taken in establishing flash-flood procedures is consideration of available climatological data for heavy rainfall. The Office of Hydrology has prepared a very useful Rainfall Frequency Atlas of the United States [2]. This technical paper provides rainfall amounts for durations of 30 minutes, 1, 2, 3, 6, 12, and 24 hours, and return periods of 1, 2, 5, 10, 25, 50, and 100 years. All forecasters should become familiar with the rainfall data available in that publication.

   Another useful climatological aid has been developed by the Techniques Development Laboratory (TDL) [3]. This publication presents probabilities of precipitation occurrence in several quantitative ranges (from .01 to 2.00 inches) for 6-hour periods. These data are available for 28 Western Region cities for the four seasons. Local Climatological Data Summaries should also be reviewed.

2. NMC Guidance. One of the basic tools for preparing forecasts of heavy rain is the QPF guidance furnished by National Meteorological Center (NMC). Man-machine-mix guidance prepared by the QPF Branch of NMC appears on NAFAX and FOFAX at various times--see current fax schedules.

QPF discussions are also transmitted on Service "C" teletype circuit. These discussions give the reasoning behind forecasts prepared by the QPF Branch. Teletype forecasts consist of coded isohyets for .25, .50, 1.00, 2.00 inches, etc., similar to corresponding forecasts transmitted on facsimile.

Thus, it can be seen that there is adequate basic QPF guidance available four times daily for various 12-hour periods. This guidance is based on numerical prognoses of RH, vertical motion, and lifted indices produced by the LFM and 7-layer primitive-equation models (see [4]). Also used in preparation of the QPFs are PE surface and 500-mb prognoses, 1000- 500-mb thickness, large-scale terrain influences, rainfall and snowfall reports, satellite observations, and radiosonde observations. An objective QPF procedure (SLYH Model) is also available to the NMC forecast unit, based on vertical motion, precipitable water, humidity and stability, the principal indicators of vertical motion being advection of the 1000- 500-mb thickness field by the 1000-mb geostrophic wind (see [5] and [6] for details). The QPF unit has also developed an operationally useful relationship between the Polar Jet Stream and heavy precipitation [7].

Objective QPF guidance is also furnished on Service "C" teletype in FOUS messages. A detailed description of FOUS guidance may be found in [8]. Since FOUS provides 6-hourly precipitation amounts, it has a format especially useful for short-period heavy-rainfall forecasting.

3. National Severe Storm Center Guidance (NSSC). A severe weather outlook is transmitted daily on NAFAX. This guidance is prepared by NSSC in Kansas City. The written version of this chart, the severe weather narrative (AC), is transmitted on Service A and RAWARC teletypewriter circuits. The purpose of the severe weather outlook is to alert all interests to the possibility of severe local storm development. While the emphasis is on severe thunderstorms and possible tornadoes, these storms are frequently associated with heavy short-period rainfall.

4. Refinement of NMC Guidance. NMC QPF guidance as noted above, while basic to forecasting heavy rainfall amounts, must be refined to periods of 6 hours or less and localized in area, especially taking into account local topography. This, then, is the principal task of the WSFO forecaster, and for which adequate procedures must be developed. This will mean use of smaller scale, shorter time range tools than those employed by NMC, namely radar, raobs, local reports, local topography and on-station developed objective aids, to name a few. Procedures based on the above will be discussed.

a. NMC Guidance. No regional bias is known to exist for NMC fax QPF; however, objective Primitive Equation Precipitation (PEP) forecasts contained in FOUS messages are known to have biases for portions of the Western Region. An example of precipitation occurrence bias for Salt Lake City is described in [9]. Forecasters are urged to make similar studies for their local areas.

b. LFM Guidance. Two difficulties arise regarding use of LFM guidance. One, the first 12-hour period is nearly half over by the time the initial 12-hour QPF is received. Second, LFM guidance has proved to be unreliable over much of the region, particularly during summer, when heavy thundershowers and local flash flooding are most likely to occur. NMC has made several changes in the relative humidity (RH) saturation value; apparently, it is difficult for NMC to define an RH saturation value that will produce good QPFs over all the United States.

5. Local Analysis. As with any other mesoscale phenomenon, detection of locally heavy precipitation requires some on-station local analysis. Techniques for small-scale analysis and prediction have been documented in [10], so will not be repeated here. Particular attention should be paid to techniques that may be helpful in delineating areas of locally heavy precipitation, such as analysis of dew points, cloud observations, areas of low-level convergence, etc.

6. Radar. This is probably the best available tool for short-range, detailed rainfall forecasting. Radar coverage is not complete over the Western Region, but is being enhanced by the addition of five local warning radars. Installation of these five at Las Vegas, Nevada; Phoenix, Arizona; Billings, Montana; Portland, Oregon; and Los Angeles, California, will be complete in early 1978. They will supplement existing NWS WSR-57

radars at Missoula, Sacramento, and Medford, plus 22 ARTC radars remoted into ARTC centers at Auburn, Palmdale, Salt Lake City, and Albuquerque. WSR-74C local warning radars have been designed to provide forecasters with even greater accuracy in their analysis of rainfall. A narrow beam width, a wavelength which will detect rainfall .01 inch per hour at 125 miles, and a display which depicts six contours of intensity are all features which aid in determining potential and probability of flash flooding. Given a synoptic situation conducive to localized flash flooding, a forecaster can then watch carefully for telltale signs of concentrated convective activity over the smallest drainage basins.

Coordinated with satellite data, radar can be especially effective. Embedded cells under extensive cloud shields can be readily detected by radar while satellite data can fill voids where radar returns are blocked out by terrain. Unfortunately, it was for this reason so few local warning radars were programmed for the West. High cost of remoting prohibited placement of radar equipment where terrain blocking was exceptionally great.

Many papers have been written on use of radar in rainfall forecasting; some are readily available in references [11-19].

In general, forecasters should be on the alert for strong quasi-stationary echoes (little movement for two or more hours). Particular attention should be paid to echoes with tops above 35,000 feet, echoes taller than surrounding echoes by more than 5,000 feet, also to rapidly growing and converging echoes and line echo wave patterns (LEWPs). By combining echo intensity with range, rainfall rates can be estimated within a factor of two or three. Radar operators will, of course, alert WSFO and WSO forecasters to echoes (in their areas of responsibility) that appear to have a potential for producing heavy rainfall. Forecasters, in turn, can alert radar operators to particular areas of concern in order that special attention can be paid to developments in that area.

7. Topographic Effects. One of the principal factors in localizing NMC QPF guidance is consideration of topographic effects. All forecasters are undoubtedly well aware of the general effect of topography on synoptic scale weather systems in their district, but for flash-flood purposes, particular emphasis must be placed on local exposure to moisture-bearing winds in the warm season. Usually these winds are from a southerly through southwesterly direction; thus mountain

ranges facing these directions are particularly vulnerable to heavy warm-season rains. However, it should be kept in mind that locally heavy thundershowers may produce flash flooding in almost any area. Direction of movement of thunderstorms over small basins is important in relation to flash flooding. In general, but dependent upon basin configuration, if a thunderstorm moves up the basin, the hydrograph is smoothed out, as runoff from the lower portion of the basin is gone before runoff from the upper basin reaches the lower portion. However, if a thunderstorm moves down the basin, the runoff peak is sharpened with upper and lower basin runoff occurring simultaneously.

Reference [20] should be helpful in determining which stations are particularly vulnerable to heavy rain under different synoptic situations.

8. Satellites: The Geostationary Operational Environmental Satellite (GOES) system is ideally suited to flash-flood monitoring and forecasting. Unlike the old polar-orbiting system which provided data over a given area only two times a day, the GOES system provides higher resolution (1/2 nm) imagery every half hour during daylight hours. Infrared (IR) imagery is available around the clock in either the standard mode or as enhanced IR data. Several sectors covering various geographical areas are available to any office on the GOES system. The GOES Users Guide [21] should be consulted for the latest enhancement tables and sections available.

Enhanced IR satellite data have recently been used to formulate an objective technique for determining rainfall rate, see [22]. The technique consists of measuring changes in cloud-top size and temperature from one picture to the next. This information plus other satellite-derived data like the presence of cell mergers, overshooting tops, etc., are used to produce an objective estimate of rainfall reaching the surface. In this sense use of the data is very similar to using radar data in that it is primarily a diagnostic technique. However, like radar, there are often on-going trends that can be used in a prognostic sense for a short-term forecast.

The other obvious advantage of satellite data is that it depicts cloud systems equally well over the entire region. Since radar suffers from poor detection over several large areas of the West, satellite imagery makes an excellent complimentary source of information to fill in "holes" in available radar coverage, see [23].

Presently time-lapse satellite imagery is available only at the Satellite Field Services Station (SFSS) in Redwood City, California. Hopefully this type of data will be available to all WSFOs within the next few years. All stations are encouraged to call the SFSS when information about detailed movement and development of cloud systems is needed. It is especially helpful to call the SFSS early on a day that the forecaster expects a flash-flood threat. This calls the attention of the SFSS meteorologist to the problem area and allows him to order special satellite products in advance of the expected activity to monitor the situation.

9. Checklist. It is particularly helpful to develop a checklist for use in flash-flood forecasting. This can serve both to alert the forecaster to the fact that a flash-flood situation is possible or may soon develop, and also to assist in preparation of the forecast itself, including items such as timing, intensity, location, etc. All parameters found to be useful for the forecast should be included in the list, from NMC guidance down to detailed variables derived from analysis of upper-air soundings. Important indices such as K value, stability index, precipitable water, condensation levels, antecedent soil condition, etc., should be graphed daily during the flash-flood season. Trends of these variables will serve to alert the forecaster as to the flash-flood potential.

B. Cut-Off Lows.

Precipitation associated with cut-off upper lows can at times be sufficiently heavy to result in flash flooding over the Intermountain Region. These lows have a maximum frequency in spring and fall, but also occur in winter and may be important over the southern portion of the plateau during this season, where rain rather than snow accompanies the cut-off low. Flash flooding may be associated with this type of low in May and June in eastern Oregon, eastern Washington, and Montana, as convective cells and feeder bands with locally heavy precipitation are frequently embedded in the circulation around the low. The strongest cells are usually found on the eastern side of the lows. Studies by TDL [24, 25, 26] provide quantitative precipitation amounts associated with different intensity 850-, 700-, and 500-mb lows during fall and winter.

C. Objective Studies.

Since flash floods are principally local in character, on-station studies of synoptic situations conducive to heavy, short-period rains should be particularly helpful. NMC objective studies referenced above and known radar-rainfall relationship could serve as examples and starting points.

Efforts should be made to identify parameters that will enable the forecaster to recognize situations leading to development of thunderstorms that are both quasi-stationary and heavy rain producers.

Parameters derived from analyses of local soundings such as precipitable water, stability indices (K factor, Showalter Index, etc.), convective and lifting condensation level, plus positive areas on the sounding associated with forecast maximum temperature, should be useful. Additional ideas for local objective QPF studies may be gleaned from the many papers written on the subject in recent years, many of which are listed in the references given in this report.

More studies are needed relating radar echo intensity to precipitation amounts. While this type of study will be most feasible at WSR-57s and 74Cs, Hall [18], has shown that switching ARTC radar from Linear Polarization (LP) to Circular Polarization (CP) mode can provide estimates of echo intensity which correlate with precipitation amounts, although echo intensity generally is limited to only two categories.

Studies relating amount of rainfall over a certain time period necessary to trigger flash floods over particular basins would be very helpful to those offices having radar. Local warning WSR-74C radars with capability of displaying only echoes of a certain intensity or continuation of intensities are especially adaptable to this approach. With other radar systems, procedures involving hand-drawn maps of hourly precipitation echoes or accumulative amounts for various time periods are very effective. Such procedures are described in some of the references at the end [11, 12, 15, 16, 27].

Postmortems of previous flash floods are especially valuable. Meteorological parameters cited above can be related to measured rainfall and runoff in this type of study.

D. Future Outlook.

A major difficulty in flash-flood forecasting is that significant features of precipitation usually exist that are not detectable in a synoptic network. Locally heavy rains, which may result in flash flooding, can be observed only in meso-networks similar to the California Marble Cone network. This network consists of self-reporting tipping bucket gages. Each millimeter of rainfall tips the bucket and actuates a radio transmitter. The transmitter signal is received at an office with 24-hour coverage. With this real-time ground-truth data available, radar and satellite data can be better interpreted in real time.

Improvements in radar are programmed now for both WSR-57 and ARTC radars which should also provide the bases for better short-fuse precipitation forecasts. A Video Integrator and Processor (VIP) has been developed for the WSR-57 radar. Up to 6 levels of echo intensity can be contoured. Individual levels of intensity, combinations of intensities or all levels can be depicted on the display at once out to 125 miles range of the scope. This is considered to be the maximum distance of significant accuracy of radar measurement of rainfall. The old time-consuming subjective method of injecting increasing levels of attenuation on certain echoes will no longer be necessary.

A similar requirement with the same capabilities has been developed for ARTC radars and will be available in late 1980. This will be particularly significant to the Western Region since most of the radar coverage is by ARTC radar. Signal Variability Processor (SVP) is a recent development which holds great promise for mountainous regions of the West. This equipment eliminates bright and confusing ground clutter from display scopes. Operators may follow precipitation patterns more effectively through ground clutter and determine those drainages and basins which will be susceptible to flash-flood producing rainfall. SVP will also make VIP more effective in determining rainfall intensity in mountainous terrain.

Radar Data Processing and Remoting Equipment (RADAP) is scheduled for delivery to Western Region WSR-57 stations in late 1983. This application of computer technology to processing of radar data will result in almost unlimited capability in determining probability of occurrence of flash floods through automatic totalizing of rainfall amounts for any time period desired. Incorporated with this will be automatic audio and visual alarms based on data reaching predetermined critical levels. With installation of AFOS, a computer will be available, which, when coupled with radar and a network of event-reporting gages may bring even greater capabilities of accurate real-time precipitation data for flash-flood forecasts and warnings.

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