NEXT GENERATION WEATHER RADAR FLASH-FLOOD POTENTIAL SYSTEM

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ABSTRACT

The Next Generation Weather Radar (NEXRAD) will be a nationwide network of weather radars designed to meet the weather mission needs of the Department of Commerce, Department of Defense, and Department of Transportation into the 21st century. For the continental United States, the National Weather Service currently plans to replace the existing basic weather radar network with 113 NEXRAD's. Deployment of the NEXRAD's will begin in the late 1980's and continue into the early 1990's. The National Weather Service's Hydrologic Research Laboratory has developed a Flash-Flood Potential (FFP) system for NEXRAD. It involves a fully automated and completely objective procedure simple enough to be done computationally every scan, yet robust enough to project adequate precipitation estimates and flash-flood probabilities for periods up to an hour in the future. The FFP system consists of three components: (1) a precipitation projection procedure; (2) a flash-flood potential assessment procedure; and (3) a product generation procedure. These components will provide: (1) short-term projections (nowcasts) of precipitation accumulation fields for up to 1 hour; (2) summed observed and forecasted precipitation accumulations for various durations; and (3) probability products of flash-flood potential. The FFP system will begin with precipitation values from the NEXRAD Precipitation Processing System and produce graphical displays, for each of the items mentioned above, for use by the local forecast offices.

INTRODUCTION

The NWS defines a flash flood as "a flood caused by a rapid rise, usually within 6 hours of the onset of a causative event, on a river or creek. Flash floods typically result from excessive rainfall, dam or levee failure, or a sudden release of water by an ice jam" (NOAA, 1985). Flash floods have occurred in every state and, generally, are the result of intense thunderstorms that produce large rainfall accumulations, over a relatively small area (25-130 km2), in short time periods.

During the past decade, floods and flash floods have become the major cause of weather-related deaths in the United States. Present statistics indicate that property losses are averaging $2-3 billion annually and that 80 to 90 percent of the 200 annual flood-related deaths are caused by flash floods. Despite the billions of dollars invested in flood-control projects since 1936, average annual flood damages continue to increase at a rate of 5 percent per year (Barrett, 1983). Flood damages continue to increase primarily as a result of continued development in the flood plains and increased urbanization of upstream watersheds. The projected growth in population is expected to cause this trend to continue unless flood-plain management is improved and significant measures are taken now to reduce flood losses. As a result, the National Weather Service (NWS) is devoting more of its energy and resources to flash-flood forecasting, with radar playing an important role, in an effort to reduce flood losses.

The primary requirement of radar for hydrological purposes is to provide estimates of the amount, and the temporal and spatial distribution of precipitation that falls over a basin. Development of procedures for using radar as a tool to measure the areal distribution of precipitation have progressed from the subjective manual techniques first used in the late 1940's, through the semi-automatic techniques, to the fully automatic techniques of today (Greene and Flanders, 1976). The Next Generation Weather Radar (NEXRAD) to be deployed in the late 1980's will be able to locate heavy rainfall centers, define storm movement, and derive rainfall estimates, all of which are of paramount importance in flash-flood forecasting.

The Radar Hydrology Group (RHG) of the NWS's Hydrologic Research Laboratory (HRL) has developed a Flash-Flood Potential (FFP) system for NEXRAD. The FFP system consists of three components: 1) a precipitation projection procedure; 2) a flash-flood potential assessment procedure; and 3) a product generation procedure. The FFP system is statistically based and has been intentionally designed to provide a compromise between those procedures which employ the full covariance structure of the fields and those which simply extrapolate the total pattern based on a simple match approach. In this way, computational efficiency is preserved, while sufficient "dynamics" of the field should be retained to capture many of the mesoscale features producing heavy rainfall and associated flash-flood potential. Procedures in the FFP system are based on experiences with real-time rainfall estimation from the Digitized Radar Experiment (D/RADEX) system, the GARP Atlantic Tropical Experiment (GATE) project, and other experimental projects, as well as an analysis of methods for improving applications of weather radar to hydrometeorology. The purpose of this paper is to describe the various components of the proposed on-site FFP system which will be implemented on the NEXRAD Radar Product Generator (RPG).

Validation of the two algorithms employing the procedures described herein is in progress and, therefore, changes in various processing details should be expected. However, at a minimum, the current specifications are representative of the computational effort required. We believe that the procedures included are those minimally sufficient to provide the accuracy required for the numerical applications of these data and to provide graphical products useful to the forecaster. Further quality control of the radar data is expected at the regional/national processing level to make use of other types of data, as well as radar data from other NEXRAD sites with overlapping coverage.

Figure 1 contains a block diagram outlining the basic steps within the on-site FFP system. We believe that this system will result in enormous benefits in improved flash-flood forecasting if quality radar-rainfall projections and flash-flood potential estimates are made available through NEXRAD.

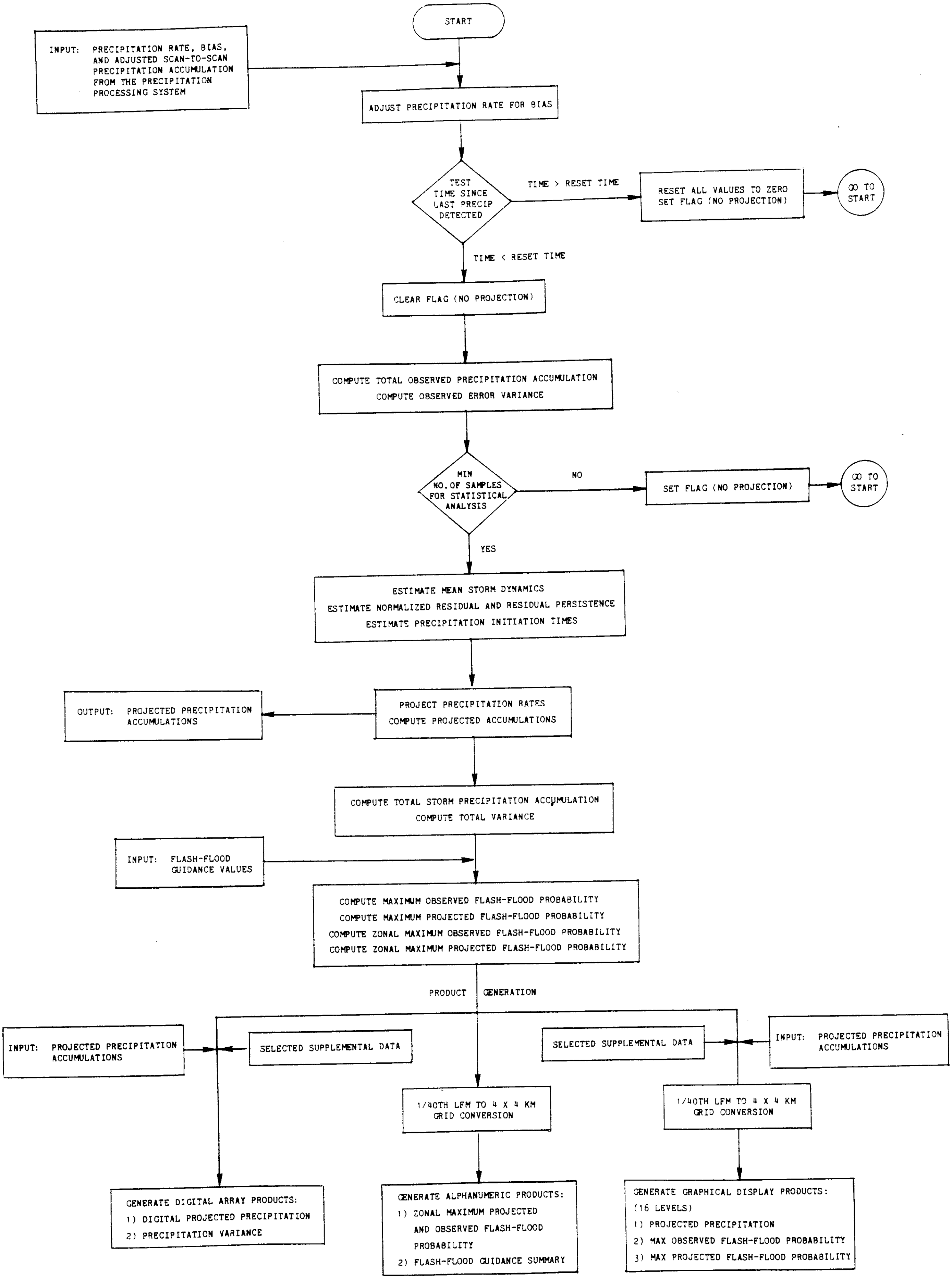

FIGURE 1 - BLOCK DIAGRAM OF THE ON-SITE FLASH-FLOOD POTENTIAL SYSTEM.

INPUTS FROM THE PRECIPITATION PROCESSING SYSTEM

The FFP system uses the current precipitation rate data and the adjusted scan-to-scan precipitation accumulation data from the NEXRAD Precipitation Processing System (PPS) (Ahnert et al., 1983, 1984) as input. The precipitation rate data coming from the PPS are on a 1 degree by 2 km polar grid from 1 to 230 km, in dBR, and has a precision of at least 0.5 dBR and a dynamic range of at least -18 to 32 dBR (dBR = 10 log (rainfall rate in mm/hr)). The adjusted scan-to-scan precipitation accumulation data are also on a 1 degree by 2 km polar grid from 1 to 230 km, but in dBA, and with a precision of at least 0.5 dBA and a dynamic range of -29 to 26 dBA (dBA = 10 log (rainfall accumulation in mm)). The adjusted scan-to-scan precipitation accumulation data has been adjusted for the estimated mean field bias, which is a multiplicative factor that adjusts for the radar bias when compared to hourly surface precipitation measurements from a limited number of automated rain gages. The FFP system adjusts the precipitation rate data for bias and converts the PPS input to linear units on a 1/40th Limited Fine Mesh (LFM) grid (approximately 4 km x 4 km).

PRECIPITATION PROJECTION PROCEDURE

The precipitation projection procedure will produce short-term forecasts of precipitation accumulations updated at scan rate intervals (approximately 6 minutes) for up to 1 hour into the future. It is based on a statistical forecasting approach and relies solely on the inputs provided by the PPS. This procedure can be broken down into four phases: 1) Estimation of mean storm "dynamics"; 2) Estimation of normalized residual and residual persistence; 3) Estimation of precipitation initiation times; and 4) Projection of precipitation accumulations.

Although the procedure is statistically based, it does not employ a full statistical approach to precipitation projection. Such techniques require the estimation of a covariance function which is quite demanding computationally. The goal is to develop a procedure that requires no more than a few million mathematical operations to be performed at each scan time, yet preserves a rich enough structure to produce adequate estimates of future precipitation for periods up to an hour in the future.

A second requirement of the procedure is that it be fully automated and completely objective. To that end, no human interaction or interpretation is required. There are a limited number of tolerance parameters which affect the procedure's performance, but these have been kept to a minimum.

1. Estimation of Mean Storm "Dynamics"

Precipitation is an extraordinarily complex phenomenon, especially so when considered at the space and time resolution of the NEXRAD radar. The task of a statistically based forecast system is to create a mathematical description of this complex phenomenon that allows forecasts to be made. The first step in such a procedure is to decompose the process into two parts: the mean value and the residual. This section describes the assumptions and procedures used to define the mean precipitation rate.

The simplest form for the mean value follows from an assumption that the mean is homogeneous in space and stationary in time. The mean is then estimated by a simple average of all reports. Although this assumption leads to a simple computation for the mean value, it requires a very complex procedure to forecast the residual.

Perhaps the most complex form for the mean value would be a microscale dynamical model of the precipitation process. The residual would contain only the results of model deficiencies and input errors, and if the model and input were perfect, there would be no residual at all. This approach leads to a very complex computation for the mean, but it may allow simple procedures to forecast the residual.

The procedure adopted here lies between these extremes. It presumes that, in the absence of any additional information, the expected precipitation rate at a specific location in space at a particular time can be estimated by the average rainfall rate at all other locations and times at which the duration of precipitation since the initiation of precipitation at each point is identical. As an example, consider a point where it has been raining for 10 minutes. The expected rainfall rate at that same point 5 minutes from now is presumed to be the average of the rainfall rates at all points where the local duration of precipitation is 15 minutes.

This mean value function evolves in time, but the time axis is translated on a point-by-point basis so that "time=0" is defined by the time when rainfall starts at each point.

The procedure, as a whole, produces a series of projected precipitation rate fields separated in time by DELT minutes. From this, a "storm counter" is defined for each value equal to the difference between the current time and the time of initiation of precipitation at the particular point all divided by DELT (and truncated to an integer value). The sample mean and standard deviation are then computed by sorting all values since the storm began so that each computation includes only those values with the same storm counter.

There are two practical difficulties with this procedure: First, it may happen that only one value exists with a particular storm counter, or more generally that too few values with a particular storm counter exist for reliable estimates of a mean and standard deviation. This difficulty is resolved simply by combining samples with storm counters one less than, two less than, ... the "problem" value until a minimum sample size criterion is met.

The second difficulty is more serious. In order to do projections into the future, the mean and standard deviation are needed for storm counters exceeding the maximum available storm counter. Although a variety of schemes for projecting the storm "dynamics" beyond the maximum storm counter are possible, initial development will assume simple persistence -- the mean and standard deviation for all storm counters beyond the maximum available storm counter are presumed equal to those for the maximum available storm counter.

The storm counter method captures some, but certainly not all, of the differences between storms. It distinguishes between a narrow fast-moving squall line and a broader slower-moving front. It reproduces the longer period of light rain which frequently follows the heavier rain near the start of a convective shower. By capturing certain distinguishing features of an event, the storm counter method reduces the burden on forecasting the residual. At the same time, the method is simple to apply and requires only minimal computational resources.

2. Estimation of Normalized Residual and Residual Persistence

The mean and standard deviation estimates derived by the storm counter method explain part of the observed rainfall pattern, but it cannot capture features such as orographic enhancements, "stalled" convective cells, cells which are more (or less) intense than the norm, etc. If the mean value of rainfall rate for each bin in an observed scan (determined by the storm counter technique) is subtracted from the observed rainfall rate, then a residual is defined. The residual divided by the standard deviation (again determined by the storm counter technique) defines a normalized residual which has by definition a mean value of zero and unit variance over the radar field. The normalized residual should capture those features described above as areas of positive and negative values.

The normalization procedure allows the residuals to be directly compared from one scan to the next to derive a single residual persistence parameter, i.e., the lag one autocorrelation of the normalized residuals.

3. Estimation of Precipitation Initiation Times

At all locations where it is raining, the storm counter is known and the residual is known; therefore, rainfall accumulations can be projected into the future. But at other locations where rainfall has not started, the storm counter is unknown. It is necessary to estimate the time of initiation of precipitation at these sites. This requires two steps -- estimation of a storm velocity and determination of starting times based on this velocity.

The procedure used to estimate the storm velocity is based on a linear regression procedure using the initiation times as the dependent variable. This procedure finds the parameters a and b in the equation:

$$t_{ij} = a\,(x_i - x_j) + b\,(y_i - y_j) \tag{1}$$

where t_{ij} = difference in storm initiation times at bins i and j;

x_i, x_j = east-west grid locations of bins i and j, respectively; and

y_i, y_j = north-south grid locations of bins i and j, respectively.

The parameters a and b are related to the storm velocity and direction. The storm velocity of this procedure is a "leading edge" velocity which is appropriate.

The straightforward procedure to estimate parameters a and b of equation (1) would be to employ a simple least squares estimate using as sample values all (i,j) pairs where precipitation has begun. This procedure gives unrealistically high values of storm velocity for two reasons: 1) it includes (i,j) pairs where the initiation at the i-th both has nothing to do with the initiation at the j-th box, i.e., box i and box j are far apart; and 2) the large amount of scatter in the sample values used in the straightforward least square analysis causes a bias toward small values of the estimates of a and b in equation (1). As a result, a somewhat more sophisticated procedure is adopted.

First, the sample values contributing to the least squares estimate of a and b are limited to boxes where precipitation has just begun and within a surrounding 7 x 7 (roughly 30 km x 30 km) region. This increases the chances that initiation at the i-th box is in fact physically related to initiation at the j-th box.

Second, the actual initiation velocity is estimated separately from the least squares estimates of a and b, and the values of a and b are scaled to this velocity. In essence, the least squares estimates from equation (1) provide the storm's direction, but the velocity is estimated separately. This estimate is simply the average of the time lag in storm initiation between all bin pairs contributing to equation (1), divided by the bin-to-bin distance.

The procedure described above would work fine if the storm's direction and velocity did not change with time or vary geographically. In order to account for temporal variation in the storm velocity, a memory parameter is introduced which gives geometrically increasing weights to more recent sample values. In essence, the procedure slowly forgets the early history of the storm. It may be valuable to regionalize the estimates of storm velocity, i.e., to estimate different storm velocities for different parts of the field of view, but this has not been implemented at this time. Such a procedure introduces thorny issues of selecting appropriate regions and projecting storm movement across regional boundaries.

Once a storm velocity estimate exists, it is relatively easy to estimate initiation times. Beginning with each point where precipitation has yet to begin, bins are searched in the "upwind" direction as defined by the storm initiation parameters a and b beginning with the closest bin. The region of the search is rectangular. The direction of the rectangle is defined by the storm initiation parameters. The length of the region is defined such that the estimated initiation offset time from equation (1) is equal to the projection time, therefore, if no bins in the search region have precipitation, it is assumed that precipitation will not occur during the projection period. The width of the search region is an exogenous parameter; the width must be fairly small -- on the order of the grid spacing -- or the region where storm initiation is estimated will "blow up" with increasing projection time. The time lag before initiation is defined directly by equation (1) applied to the closest upwind point where the storm has begun (if any).

With the storm initiation times either known or estimated at all points, the storm counter is defined at all points as (current time - initiation time)/DELT. The storm counter will be a negative number at locations where precipitation has not yet begun, since the projected initiation time is larger (later) than the current time.

At locations where rainfall has not yet begun, the normalized residual is taken equal to the normalized residual of the closest upwind point where the storm has begun (if any).

4. Projection of Precipitation Accumulations

At this point in the procedure, the storm counter and the normalized residual are known for every point and the mean precipitation rate and standard deviation are known for each storm counter value. With this information, it is possible to create a projected precipitation rate for any time in the future.

First, the projected normalized residual is estimated for each bin based on the residual persistence model described in subparagraph 2. This is simply the current normalized residual, times the residual persistence parameter raised to a power equal to the number of time steps into the future. The mean and standard deviation are indexed at each point by the current storm counter plus the number of time steps into the future. Finally, the projected precipitation rate is simply the mean rate, plus the projected normalized residual times the standard deviation.

This process is repeated for each time step of the projection period to create a time series of projected precipitation rates for each point. Accumulations for the projection period are computed from these rates.

5. Computation of Error Variances

The procedures described above compute the expected value of precipitation rates and accumulations both in the past and future (in essence, the conditional mean), but it is essential to recognize that these estimates, especially the projected values, are far from perfect. In order to support the computation of flash-flood probabilities in the assessment procedure, it is necessary to estimate error variances for both observed and projected precipitation accumulations. These error variance computations are actually integrated into the four-part projection process, but they are described in a separate section to simplify the exposition.

Errors in radar-derived precipitation estimates are due to numerous sources, and a full error variance computation that explicitly recognizes each error source would be computationally very demanding. The precipitation processing subsystem attempts to remove many of these sources of error, but even so, it does not guarantee perfect estimates. The major factors to be considered in the estimation of the observed error variance are:

a. Errors (in linear units) will tend to be larger when rainfall rates are larger.

b. Errors will tend to be larger in regions of large gradients in reflectivity.

c. Errors will tend to increase at increasing ranges.

d. Errors should be proportional to the magnitude of the adjustment factor estimated in the precipitation processing subsystem by comparison to rain gage data.

The observed error variance at a point is assumed to be proportional to the local variance in estimated precipitation rates within a 5 x 5 bin region (roughly 20 x 20 km). The error proportion factor is an adaptation parameter. Since the estimated precipitation rates themselves contain range and bias corrections, this computation implicitly includes these effects. The local variance will also tend to be larger in areas with high gradients and higher precipitation rates so that these factors are implicitly included.

The error structure for the projected rates is considerably more complex. It must account for three types of error: those due to the fundamental observation error as described above, those due to the projected mean rate, and those due to the projected residual. These three error sources are considered to be uncorrelated with each other and are estimated separately. The projected error component due to observation error is simply taken to be the most recently computed observation error variance. The projection error component due to errors in the mean is simply taken from the well-known variance of the sample mean for each storm counter. The assumed form of the residual persistence allows computation of the error variance of the projected residuals. Although the observation errors and the error in the projected mean rates are assumed to be uncorrelated in time, the errors in projected residuals are clearly correlated. This would not affect the computation of an error variance for an individual projected rainfall rate, but what is required is the error variance of accumulations, not rates. As a result, the full covariance matrix of the rainfall rates contributing to any accumulation is required.

FLASH-FLOOD POTENTIAL ASSESSMENT PROCEDURE

Accurate assessment of flash-flood potential involves both meteorological and hydrological considerations. The quantity of rainfall deposited at the surface over some time interval provides a measure of the potential runoff that might be expected, but precise estimates of streamflow can be determined only if information on soil moisture conditions and watershed characteristics are known. The flash-flood guidance values issued by the NWS River Forecast Centers (RFC's) are based on pre-runs of hydrologic models which take into account soil moisture and watershed characteristics. The flash-flood guidance values derived from the hydrologic models are the rainfall amounts, over specified durations, required to produce flooding. Flash-flood guidance values are presently being issued for counties and public warning zones. They are updated once a day by the RFC's and will be communicated to the NEXRAD RPG using the existing rain-gage data acquisition port.

The flash-flood potential assessment procedure uses flash-flood guidance values developed by the RFC's, and observed and projected precipitation accumulations output by the precipitation projection procedure to produce observed and projected flash-flood probabilities. Such flash-flood potential assessment procedures have been developed or proposed in previous work by a number of researchers (for example, Zevin and Davis, 1985; Newton and Norman, 1985; Henz, 1980; and Wasserman, 1975).

The procedure calculates the observed and total storm precipitation (observed plus projected) accumulations and error variances for the various flash-flood guidance durations. The flash-flood guidance values are then compared to these accumulations, and an observed and projected probability of flash flooding is computed for each 1/40th LFM grid box. The flash-flood probability is the probability that a random variable sampled from a normal probability distribution, with a mean and variance equal to the precipitation accumulation and variance for a flash-flood guidance duration, will exceed the flash-flood guidance value for that duration. This approach is similar in some respects to the one proposed by Zevin and Davis (1985).

The procedure can handle up to three different flash-flood guidance durations, with the maximum duration being limited to 6 hours. The maximum projected and observed flash-flood probability among all the flash-flood guidance durations for each 1/40th LFM grid box and for each guidance zone are output by this procedure to produce the flash-flood probability products described in the following section.

PRODUCT GENERATION/DISTRIBUTION

The FFP system will generate data array, graphic, and alphanumeric products. The data array products are intended for numerical use at computer facilities external to the NEXRAD system itself. They maintain the full dynamic range and full precision of the data used to generate the product. Data are on a "universal" grid so that data from multiple sites is immediately compatible for rapid mosaicking and communication loadings are reduced. The grids used are supersets of the LFM grid commonly used by the NWS which is based on a polar stereographic projection (Ahnert et al., 1981; Greene and Hudlow, 1982; NWS, 1980).

After compaction to further reduce communication loadings, these data will be transferred to other computer facilities at the RFC's and Weather Service Forecast Offices (WSFO's) for use in automated forecasting models and procedures. The data array Products are described below:

1. The Digital Projected Precipitation will provide, in compressed form, the projected precipitation on a 131 x 131 1/40th LFM grid (approximately 4 km x 4 km).

2. The Digital Precipitation Variance will provide, in compressed form, the projected and observed error variance on a 131 x 131 1/40th LFM grid. Selected supplemental data will also be included and may consist of the following:

a. Projection parameter

b. Storm velocity parameters

c. Storm "dynamics"

The selected supplemental data will serve as part of the information for performing additional quality control and data adjustment steps before the data are input to hydrometeorological procedures. In addition, these data will be displayable at the Principal User Processing (PUP), for use by the forecaster in assessing the quality of the FFP system products.

The graphical products are intended primarily for color graphic displays (at least two) available at each NEXRAD PUP and are available upon request. Each NEXRAD site will be able to support up to 16 PUP's simultaneously. The display will have at least a 640 x 512 pixel resolution and 16 color levels. The product display function will include the following capabilities (NEXRAD, 1984):

1. Background map selection

2. Recentering

3. Magnification

4. Time lapse display

The precipitation graphics products will be displayed on a 4 km x 4 km grid out to 230 km and have up to 16 color levels. These products are briefly described below:

1. The Projected Precipitation Product will provide the projected precipitation for up to 1 hour into the future and will be updated every scan (approximately every 6 minutes).

2. The Maximum Observed Flash-Flood Probability Product will provide the maximum observed flash-flood probability and will be updated every scan.

3. The Maximum Projected Flash-Flood Probability Product will provide the maximum projected flash-flood probability and will also be updated every scan.

The alphanumeric products will provide flash-flood probability information in a form suitable for display on both graphic and alphanumeric display devices and are described below:

1. The Flash-Flood Guidance Summary Product will provide, in an alphanumeric table: the guidance value, zonal maximum observed precipitation accumulation, and zonal maximum total storm (observed and projected) precipitation accumulation for each guidance value duration in each flash-flood guidance zone. This product will be updated every scan.

2. The zonal maximum Flash-Flood Probability Product will provide, in an alphanumeric format, the zonal maximum observed and projected flash-flood probabilities. This product will also be updated every scan.

All of the above products, or some combination thereof, will be made available to the RFC's and to the WSFO's.

With the above set of products, and the observed precipitation accumulation products from the PPS, the forecaster can monitor the accumulated precipitation for various durations up to the current time, evaluate precipitation forecasts for short periods into the future, noting areas of potential heavy rainfall, and assess flash-flood potential through the use of the flash-flood potential products and other information. Map backgrounds stored at the NEXRAD PUP, e.g., county and basin boundaries and stream locations, will further enhance the usefulness of the graphic displays produced by the FFP system. The products produced by this procedure should be viewed by the forecasters as very useful guidance, but not as definitive identification of flash flooding until interpreted together with other information at their disposal.

LIMITATIONS

Although this comprehensive FFP system provides a framework for achieving quality precipitation projections and flash-flood probabilities from NEXRAD, the products generated do not explicitly take into account the following conditions:

1. Precipitation areas moving in widely varying directions at the same time.

2. Curvilinear storm motions.

3. Individual cell dynamics other than that accounted for by the current residual field.

4. Initiation of precipitation other than due to the motion of existing precipitation areas.

5. Long-term mean residuals at each location in the grid.

Other limitations arise from the use of flash-flood guidance values which:

1. Do not reflect criteria for urban areas.

2. Are not calculated the same way at all RFC's.

3. Are calculated from data bases that may not allow the RFC's hydrologic models to accurately reflect soil moisture conditions, for all areas within a zone, in the computation of flash-flood guidance values.

4. Are presently only updated once a day and do not have an updating procedure to reflect changes brought about by multiple rainfall events.

FUTURE DEVELOPMENTS

The most important task, which is in progress, is the complete verification of this system using real data. Current plans are to use a 5-¼ hour case acquired as part of the Prototype Regional Observing and Forecasting Service's (PROFS) summer 1983 forecasting exercise from the National Center for Atmospheric Research (NCAR) CP2 radar. The CP2 radar has technical characteristics similar to those planned for NEXRAD. A follow-up paper will emphasize the results of these tests and assess the operational readiness of the proposed NEXRAD FFP system.

This system is only part of the overall NWS program to improve flash-flood forecasting. A system at the WSFO called Forecasting and Local Analysis System for Hydrometeorology (FLASH) is presently being developed within the NWS. FLASH will use the observed precipitation from the NEXRAD PPS and projected precipitation from the NEXRAD FFP, along with other data, to produce site-specific flash-flood forecasts.

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