NOAA Technical Memorandum NWS HYDRO 44

MODERNIZED AREAL FLASH FLOOD GUIDANCE

Office of Hydrology
Silver Spring, Md.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

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TABLE OF CONTENTS

ABSTRACT 1

1. INTRODUCTION 1
   1.1 Definitions 1
   1.2 Current Methods 2
   1.3 Current Problems 2

2. IMPROVEMENTS for NWS MODERNIZATION 5
   2.1 Requirements 5
   2.2 Policy 5

3. PRODUCTION OF GUIDANCE AT THE RIVER FORECAST CENTERS . . 6
   3.1 Types of Guidance 6
   3.2 Components of Guidance 6
      3.2.1 Threshold Runoff 6
      3.2.2 Current Soil Moisture Conditions 9
   3.3 Computing Guidance 11
   3.4 Intensity 11

4. USE OF GUIDANCE AT THE WEATHER FORECAST OFFICES 12
   4.1 Gridded Guidance 12
   4.2 Headwater Guidance 12

5. USE OF GUIDANCE BY LOCAL COMMUNITIES 13

6. TECHNICAL OVERVIEW 13
   6.1 Threshold Runoff 13
   6.2 Flash Flood Algorithm 16

7. SOFTWARE REQUIREMENTS 17
   7.1 Threshold Runoff 18
   7.2 FFG Operation for OFS Version 5 18
   7.3 Flash Flood Guidance Execute Program 18
   7.4 Message Generation Program 19

8. RESOURCES 19

9. TEST AND EVALUATION 19

10. FUTURE IMPROVEMENTS 20

11. ACKNOWLEDGEMENTS 21

12. REFERENCES 21

Appendix A: DERIVATION OF THRESHOLD RUNOFF A-1

Appendix B: HEADWATER FLASH FLOOD GUIDANCE B-1

MODERNIZED AREAL FLASH FLOOD GUIDANCE

Timothy L. Sweeney

ABSTRACT

The National Weather Service (NWS) must establish uniformity in determining flash flood guidance (FFG) for small streams in counties and urban areas to take advantage of the approaching availability of both the Advanced Weather Interactive Processing System (AWIPS) and much finer resolution precipitation estimates from the WSR-88D radars. This paper describes the development and enhanced procedures at the River Forecast Centers (RFCs) for generating areal FFG for small streams. The goal is for more accurate and more consistent areal FFG based on (1) a uniform and objective method of deriving threshold runoff and (2) a standard algorithm to compute flash flood guidance.

1. INTRODUCTION

The use of areal flash flood guidance has increased since it was first implemented by the NWS in the mid 1970's. Flash flood guidance along with observations and/or forecasts of rainfall are used by the forecasters at the Weather Service Forecast Offices (WSFOs) to determine when to issue flash flood watches and warnings.

1.1 Definitions

An understanding of the terminology used in the NWS program will hopefully eliminate the misunderstanding and confusion that sometimes exist in the interpretation of current, as well as future, flash flood guidance products. Some definitions are listed below:

> **Flash Flood** - A flood which follows within generally less than six hours of heavy or excessive rainfall.
>
> **Flash Flood Guidance** - The general term which refers to the average rain needed over an area during a specified period of time to initiate flooding on small streams in an area. The term also includes the average rain needed over an area during a specified period of time to initiate flooding at a specific location (i.e., headwaters and other downstream locations where a vertical reference exists) immediately downstream of the area.

Areal Flash Flood Guidance - The average rain needed over an area during a specified period of time to initiate flooding on small streams. Currently specified for a public forecast zone, county, or urban area and for grid bins used with AWIPS in the future.

Zone Guidance or **Zone Flash Flood Guidance** - The average rain needed over an area during a specified period of time to initiate flooding on the small streams in an area defined as a public forecast zone.

County Guidance or **County Flash Flood Guidance** - The average rain needed over an area during a specified period of time to initiate flooding on the small streams in an area defined as a county.

Urban Guidance or **Urban Flash Flood Guidance** - The average rain needed over an area during a specified period of time to initiate flooding in an area defined as an urban area.

Site-Specific Guidance, Headwater Guidance, or **Headwater Flash Flood Guidance** - The average rain needed over an area during a specified period of time to cause a stream to rise to flood stage at a location having a vertical reference. The area is immediately upstream of the location which is usually a headwater but can be a downstream location, too.

Threshold Runoff - Runoff (in inches) from a rain of a specified duration that causes a small stream to slightly exceed bankfull. When available, flood stage is used instead of slightly over bankfull. (Appendix A contains the technical definition.)

1.2 Current Methods

River Forecast Centers have always maintained their own software for generating areal FFG. As a consequence, areal FFG is calculated using various methods that are not consistent among the RFCs. Current products include at least 3-hour FFG for zones. Some RFCs issue 1-, 3-, 12-, and 24-hour FFG for both zones and counties. FFG products are generally issued only once a day during late morning to early afternoon. Figure 1a shows the current features.

1.3 Current Problems

The inconsistencies in areal FFG between adjacent areas, especially at RFC boundaries, reflect several problems with current areal FFG methods. These problems are related to

threshold runoff, use of different rainfall-runoff models, precipitation data network density, and limited capability for enhancements. These problems and related issues are described in the following paragraphs.

Feature	a. Current	b. Phase 1 (IOC)	c. Phase 2
Threshold Runoff	Broad-scale Threshold Runoff (R) *	Gridded Threshold Runoff	Gridded Threshold Runoff
Moisture Conditions	RFC Basin Accounting Model using Mean Areal Precipitation (MAP)	RFC Basin Accounting Model using MAP for Grids (MAPX) *	RFC Future Accounting Model using MAPX, Soil Type, & Land Use *
Guidance Method	Several Flash Flood Guidance (FFG) Algorithms using Antecedent Precipitation Index (API) & Sacramento Soil Moisture Accounting (SACSMA) Models	Common FFG Algorithm (API & SACSMA) *	Common FFG Algorithm (future Accounting Model)
		Intensity *	Intensity
		Gridded FFG *	Gridded FFG
External Messages	Zone, County, Urban FFG in Standard Hydro-meteorological Exchange Format (SHEF)	Zone,County Urban FFG in SHEF	Zone,County Urban FFG in SHEF

Figure 1. Steps to Modern Areal FFG. Asterisks (*) denote new or modified feature from previous column.

The non-uniform procedures for deriving threshold runoff undoubtedly account for many of the inconsistencies in areal FFG values. Currently threshold runoff is defined on a broad-scale basis, e.g., only four values are used for much of one NWS region while another region has defined a value for each public forecast zone and county. In some regions, the assumptions are now unknown as to how the values were determined. In other regions, threshold runoff values were interpolated from a map of the runoff required to reach flood stage at selected headwater basins. Within regions or RFC areas, there are abrupt changes (0.1 up to 3.0 inches) in threshold runoff values. There are similar or greater changes between regions. Therefore, a

nationally consistent method of computing threshold runoff values for mountainous terrain, arid areas, and plains is strongly needed. Some differences in areal FFG across boundaries can be valid, such as difference of hydrologic characteristics on each side of the divide between two major river basins.

The use of different rainfall-runoff models by the RFCs adds to the complexity of generating areal FFG. RFCs' areal FFG software include similar algorithms, but there is no provision to assure that these algorithms calculate comparable areal FFG values.

Even though some RFCs use a snow model in their routine forecasts, at least one RFC adjusts their areal FFG, if sufficient forecast rain were assumed to completely melt the snow pack, by reducing the areal FFG by an amount equal to the water content of the snow. Today, because of the uncertainties associated with melting the snowpack, other RFCs generally do not utilize this capability.

Areal FFG is calculated with the assumption that streams are at low or insignificant flows. At least one RFC uses a manual, subjective method to lower the threshold runoff used in the areal FFG calculations when streams are at high levels.

The density of the rain gage network varies considerably. Some basins may not even have a single rain gage while others may be densely sampled by radio reporting rain gages.

The intensity of rainfall would enhance areal FFG. Generally, a short, intense rain event will produce more runoff than a rain event of equal magnitude occurring over a longer period of time. Most RFCs compute and issue areal FFG for 3 hours with no consideration of intensity. In an effort to address the intensity factor, RFCs in one NWS region include the 1-hour value, too.

Ideally, areal FFG should be updated after each rainfall event. Unfortunately, present RFC software is only able to make updates once a day and usually not until several hours after 12Z data are available.

Areal FFG is currently produced for public forecast zones, counties, and urban areas. In the future, rainfall estimates will be produced on a gridded basis by merging gage, WSR-88D data, and satellite data. A Flash Flood Potential algorithm is being implemented to combine gridded FFG values and gridded rainfall estimates to generate a map showing the probability of rainfall exceeding FFG at each grid bin. For this and other applications in the modernized NWS, it will be beneficial to produce areal FFG on a gridded basis.

In summary, current methodology for calculating areal FFG is inadequate. Improved procedures must be developed to meet the needs of the modernized NWS.

2. IMPROVEMENTS for NWS MODERNIZATION

Past efforts to introduce uniform areal FFG methodology in the NWS have met resistance. With the approaching availability of both AWIPS and the much finer resolution precipitation estimates from the WSR-88D radars, the time has come in the NWS to establish uniform procedures for areal FFG for small streams as well as headwater flash flood guidance for gaged locations. With these new procedures, RFCs will continue to be able to use various rainfall-runoff models.

2.1 Requirements

Modernized Flash Flood Guidance requirements for the Initial Operating Capability (IOC) should be as shown in Figure 1b. These include (1) gridded threshold runoff, (2) RFC basin accounting model with basin average precipitation based on gridded precipitation using MAPX, (3) a common FFG algorithm, (4) intensity factor, (5) gridded output, and (6) user output in SHEF for government agencies. Implementing these requirements will establish uniform procedures and introduce additional capabilities not now available. This is Phase 1 of a two-phase improvement program. In Phase 2 (Figure 1c), the rainfall vs. runoff curve from the basin hydrologic accounting model will be adjusted by sub-basin based on gridded precipitation using MAPX and on soil type and land use.

This paper focuses on areal FFG, but includes headwater FFG in Appendix B because areal FFG and headwater FFG share algorithms. The inclusion of headwater FFG has minimal impact on the development effort for modernized areal FFG. Both need major improvements to meet the needs of the modernized NWS.

2.2 Policy

At the FFG meeting in November 1989, which was attended by representatives from the Office of Hydrology, Office of Meteorology, and all regions in the contiguous states, the decision was made to implement uniform and improved methodology to compute areal FFG for 1, 3, and 6 hours with the capability to update every 6 hours. Areal FFG will be computed on a grid for better detail and compatibility with radar-based precipitation estimates.

3. PRODUCTION OF GUIDANCE AT THE RIVER FORECAST CENTERS

3.1 Types of Guidance

Part of the mission of the National Weather Services's (NWS) River Forecast Centers (RFC) is the preparation and distribution of flash flood guidance products. These products contain the rainfall amounts required to produce flooding, and are used by the Weather Forecast Offices (WFOs) as the criteria for issuing flash flood watches and warnings and as the current moisture conditions for support to site-specific hydrologic forecast models available in the WFO.

Flash flood guidance values are computed for small streams in an area, e.g., a grid bin, county or urban area, and for headwaters and additional points downstream where flooding is a problem. Guidance values for small streams in an area are referred to as gridded, county, or urban area guidance depending on the actual area of interest. Guidance values for headwaters and additional locations downstream are referred to as headwater guidance or site-specific guidance.

3.2 Components of Guidance

Regardless of the types of guidance, two values are required to compute flash flood guidance for a desired area: (1) The runoff required to initiate flooding, and (2) the current soil moisture conditions. Each of these are discussed in the following sections.

3.2.1 Threshold Runoff

The amount of runoff needed over an area to initiate flooding is the threshold runoff. Threshold runoff depends on several characteristics of the watershed and the stream channels. The size of the watershed (area) determines the total volume of water that appears downstream. The slope of the channel and roughness of the steambed controls the speed of the water as it moves downstream. For instance, a steep slope causes higher velocities, and a smooth streambed offers less resistance to flow. A rough streambed containing large rocks and trees resists the flow of water and slows the flow. The shape and size of a channel's cross section determines its capacity at a location along the stream. A narrow channel with low banks will hold less water than a wider channel with the same low banks. A wide channel with high banks has even a greater capacity.

Two methods are used to derive threshold runoff depending on the desired type of guidance (gridded and headwater). The methods are described in the following sections.

Gridded Threshold Runoff - In reality there are many more smaller headwaters or sub-basins that are too numerous to gage. In many cases these sub-basins seldom cause flood problems themselves, but the accumulated flows downstream become flood problems. The computation of threshold runoff for these sub-basins is more complex because there are no flood stages, rating curves, and unit hydrographs available that define characteristics of the sub-basins. It is important hydrologically to maintain physical relationships between threshold runoff and a drainage area. For this reason, threshold runoffs must explicitly represent runoff from actual hydrologic areas to support the interpolation to a grid.

Physical representations of these basins (e.g. stage ratings, slopes, unitgraphs) will be generated that will minimize the subjective factor in deriving threshold runoff. With the increasing use of geographical information systems (GIS) and digital elevation models (DEM), threshold runoff will be defined for areas smaller than the RFC's forecast basins. These sub-basins will be determined by an algorithm based on size of catchment, drainage network, and channel capacity. Threshold runoff software will determine geographic locations (sub-basins) on the streams and compute threshold runoffs for these sub-basins as indicated by the dotted lines in Figure 2. Starting upstream, a GIS locates all stream junctions using a sub-basin area of 6 to 12 mi^2 (16 to 33 km^2). Next, the threshold runoff is computed for each of the sub-basins.

After the threshold runoff has been computed for the sub-basins, the Hydrologic Rainfall Analysis Project (HRAP) grid (Schaake, 1989) is overlaid on the sub-basins (shown in Figure 3) and the threshold runoff values are computed for each grid bin.

In the future the gridded threshold runoffs derived from the GIS will be adjusted based on experience in the use of the FFG system and information obtained from site inspections as time allows. Figure 1b shows the gridded threshold runoff values.

Headwater Threshold Runoff - RFC models are based on geographical drainage areas referred to as RFC forecast basins. Most basins that have a history of flood problems are more likely to be gaged, and those flood-prone basins that are headwaters are always gaged. Describing the method to derive threshold runoff for a headwater is easier because parameters have been defined. As a result threshold runoff is a simple computation. The flood stage has been established, and the channel is defined at the

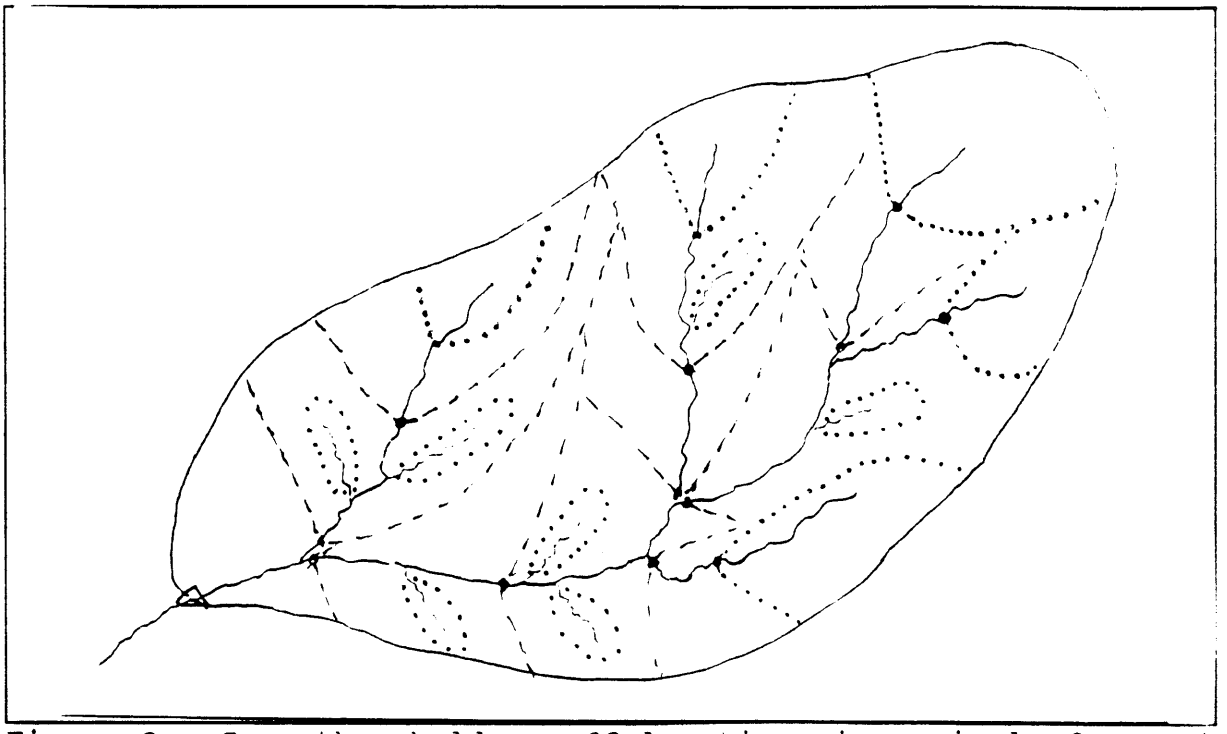

Figure 2. Some threshold runoff locations in a single forecast basin.

cross section by a rating curve that relates the depth of the water in feet (ft) to the amount of flow in cubic feet per second (cfs) in the channel. The flow in cfs at flood stage is determined from the rating curve. The slope, roughness of the streambed, and area of the watershed are incorporated in the unit hydrograph concept. The unit hydrograph relates stream flow as a function of time for one inch of runoff uniformly distributed over the drainage area for a storm of a specified duration. The peak value of the unit hydrograph is used. Finally, threshold runoff for a headwater is the flow at flood stage divided by the unit hydrograph peak for a specified duration. Only when the flood stage, rating curve, or unit hydrograph peak is changed, will the threshold runoff need to be recomputed.

A GIS and DEM can be used to locate additional headwaters on ungaged streams. Starting upstream a GIS locates all stream junctions using a sub-basin area of at least 5 km^2 as indicated by the dotted and dashed lines in Figure 2. Next the total area is computed upstream of each junction. If the total area upstream of each junction is less than about 775 mi^2 (2000 km^2), then the threshold runoff is computed for the location. The threshold runoff is not computed for areas larger than 775 mi^2 because uniform distribution of rainfall over the area is less

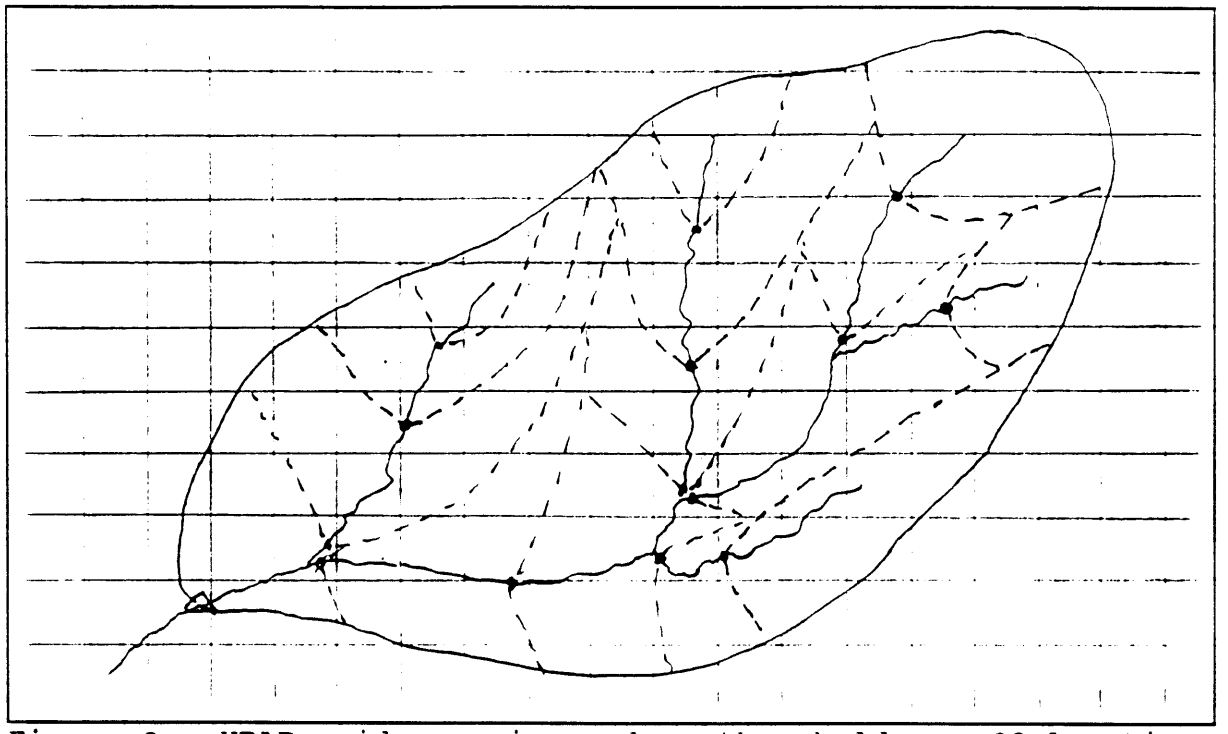

Figure 3. HRAP grid superimposed on threshold runoff locations (sub-basins).

likely and larger areas exhibit fewer characteristics of flash floods. Since headwater threshold runoff is desired, a bankfull or flood stage flow and a unit hydrograph peak flow are needed. Bankfull flow can be approximated by the two year return period flow. The unit hydrograph peak is derived from an equation as described in Section 6.

3.2.2 Current Soil Moisture Conditions

Most RFCs use the National Weather Service River Forecast System (NWSRFS) to simulate soil moisture conditions. This Operational Forecast System (OFS) uses observed precipitation and temperature to determine the mean areal precipitation and snowmelt over the forecast basins. Soil moisture parameters in the model convert the precipitation and snowmelt to runoff which is verified by observed stream stages. The current soil moisture parameters are desired for flash flood guidance computations.

A FFG operation will be added to NWSRFS to retrieve the current soil moisture parameters. The FFG operation would use any rainfall-runoff model in current RFC forecast procedures. A FFG operation would have several advantages over current individual RFC procedures. First, areal FFG would be generated more frequently than once per day and not require that the RFC store

soil moisture conditions for execution of the forecast model the next day. Second, snowmelt would be included in areal FFG computations. Third, procedures would be uniform to the extent possible, given the different rainfall-runoff models used by the RFCs (several Antecedent Precipitation Index (API) models, the Sacramento Soil Moisture Accounting models (SACSMA), and future models). Differences among the rainfall-runoff models are based on differences in soil type and land use of the various forecast basins. Furthermore, a single model must simulate several soil types and land uses within an RFC. Fourth, snowmelt could contribute significantly towards runoff during rain-on-snow events at high temperatures, thus significantly reducing the areal FFG value, especially for the 6-hour time interval. Currently, snowmelt is not considered in areal FFG computations except as it affects soil moisture conditions. Fifth, if frozen ground or other new features were added to the RFC procedures, these features would immediately be available for generating areal FFG.

The FFG operation would generate rainfall-runoff curves for each river forecast basin where areal FFG is desired. Using model representations of the current soil moisture and snow conditions from the database and forecast temperatures (if snow is included), several rainfall values would be selected and corresponding runoff values would be computed to define a rainfall-runoff curve for each river forecast basin. A typical rainfall-runoff curve for a single duration is shown in Figure 4. Curves for 1-, 3-, and 6-hour duration (12 and 24 hour optional) would be computed and written to the database. The FFG operation would only be executed when FFG output was specified in NWSRFS.

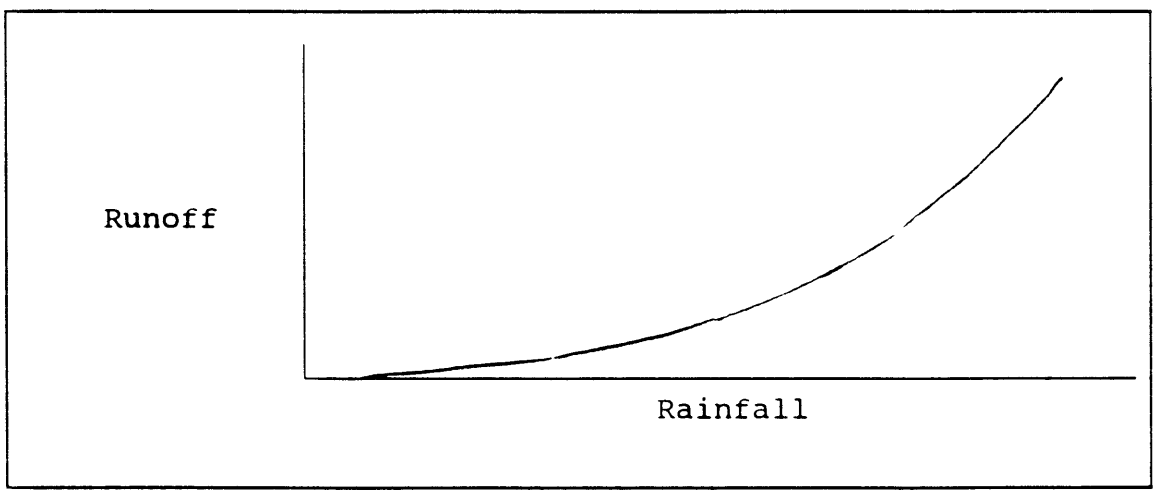

Figure 4. Typical rainfall-runoff curve for a specified duration.

3.3 Computing Guidance

When the parameters for gridded threshold runoff were defined, each grid bin in each basin boundary definition was related to a specific river forecast basin for current soil moisture conditions. These soil moisture conditions are represented by rainfall-runoff curves generated by NWSRFS. Using the threshold runoff values, FFG values are interpolated from the appropriate rainfall-runoff curves and stored in the data base.

3.4 Intensity

Under certain conditions, rainfall intensity dominates the computation of areal FFG. The procedure for computing areal FFG should involve a combination of FFG based on snow and rainfall-runoff models and FFG based on rainfall intensity. In certain parts of the country, FFG values should be based totally on intensity. In other parts, the values computed by the rainfall-runoff model would always be used. In some areas, a combination of the two methods would provide the best results. In many places where the rainfall-runoff model would normally give the best areal FFG value, intensity would be used to control the upper limit that areal FFG could attain (the value under dry conditions). In other areas, where intensity dominates, the intensity-based FFG value might be varied slightly as a function of the rainfall-runoff FFG value (soil moisture conditions). In addition, intensity-generated FFG values would tend to dominate the 1-hour time interval, and rainfall-runoff model produced values would become more important as the time interval increases. It may be difficult to determine the best combination of the FFG values produced by the two methods, but such a procedure is needed if meaningful values are to be generated for the entire country. The intensity factor is included as a new feature in Figure 1b.

There are three general conditions when intensity is dominant. These are: first, in arid areas or under drought conditions; second, in areas with relatively high soil permeabilities where interflow and baseflow are the only modes of runoff generation when examining an RFC-sized runoff zone; and third, in highly impervious areas. Under all of these conditions, flash floods generally occur from relatively small, highly convective, intense storms. Existing NWS rainfall-runoff models do not model surface infiltration so that runoff for such storms would be significantly undercomputed in the first two cases. Special procedures are needed to compute areal FFG in these situations. These procedures may initially be rule-of-thumb approaches and later evolve to more technically based algorithms. In the first and third conditions, the intensity value could be initially

approximated as an arbitrary but significant portion of the threshold runoff value. Intensity is a dominant factor in flash floods in the Great Plains, Rocky Mountains, portions of the upper Midwest, Florida, coastal areas of the Southeast and Gulf of Mexico, and in highly impervious portions of urban areas.

4. USE OF GUIDANCE AT THE WEATHER FORECAST OFFICES

The Weather Forecast Offices (WFOs) are responsible for issuing flash flood watches and warnings and specific stage forecasts for streams in their areas of responsibility. The issuance of watches and warnings is based on gridded (county) flash flood guidance information issued by the RFCs. Headwater flash flood guidance information is used in hydrologic forecast models in the WFOs that provide stage forecasts for fast response streams.

4.1 Gridded Guidance

The Weather Forecast Office (WFO) issues flash flood watches and warnings as hydrometeorological conditions warrant. The WFO forecaster compares flash flood guidance values with both observed and forecast rain over an area to determine whether to issue a watch or a warning.

Using the AWIPS console, gridded flash flood guidance will be displayed graphically with other parameters such as WSR-88D-based precipitation. The RFCs will send areal FFG as gridded values (average over the grid) to the WFOs. At the WFO, the Flash Flood Potential algorithm will compare the gridded FFG values with gridded values of observed and/or forecast precipitation (averages over the grid). Gridded forecast precipitation will be the one-hour projected precipitation from the WSR-88D grid and gridded QPF from the WFO. A display will show a color-coded presentation of the grid bins. A range of colors will represent how much the observed and/or forecast precipitation differs from the FFG value. From this display with a political boundary background (e.g., counties) the WFO forecaster will delineate a desired hydrometeorological area to issue a watch or warning.

4.2 Headwater Guidance

The WFOs also issue site-specific forecasts including warnings for headwaters as hydrometeorological conditions warrant. The Site-Specific Hydrologic Predictor System (SSHPS) is the on-site WFO hydrologic forecast model that assimilates observed and forecast precipitation with current soil moisture conditions to provide forecast river stages. The SSHPS obtains current soil moisture conditions from headwater guidance or model state variables issued by the RFCs. Observed and forecast

precipitation is obtained from the WFO's WSR-88D radar. Observed river stages are available at the WFO.

The SSHPS generates forecast river stages as a time series which is input to the River Product Formatter. The River Product Formatter generates products from the forecast time series. (This Product Formatter also generates products from forecast time series issued by the RFCs.) These products are transmitted to local news media and water managers.

5. USE OF GUIDANCE BY LOCAL COMMUNITIES

Many communities operate local flood warning systems that provide local water managers the capability to determine river forecasts based on various forecast rain scenarios. These forecast models are maintained by the RFCs and depend on FFG values for current soil moisture conditions. To honor agreements with many communities that operate local flood warning systems, county, urban, and site-specific FFG products will continue to be issued by the RFCs using the Standard Hydrometeorological Exchange Format (SHEF).

With improved communications the local flood warning systems will be modified to accept the soil moisture variables from the RFC forecast models. The soil moisture variables would be sent in an efficient format on AWIPS.

6. TECHNICAL OVERVIEW

6.1 Threshold Runoff

For a standard unit hydrograph, basin lag is a function of basin size, shape, and slope; i.e.,

$$t_p = C_t \left(\frac{L L_c}{\sqrt{S}} \right)^b \qquad (1)$$

where t_p is the basin lag in hours, defined as the time from the centroid of rainfall to the peak of the unit hydrograph; C_t is the coefficient to be derived from gaged watersheds in the same region (generally varies from 0.35 for valley areas, 0.72 for foothill areas, to 1.2 for mountainous areas); L is the main stream length in miles from outlet to basin boundary; and L_c is

the stream distance in miles from outlet to the point on the stream nearest the catchment centroid; S is the weighted channel slope throughout the drainage area in feet per mile; b is a constant assumed to be 0.38 (Linsley, et.al., 1982).

The unit hydrograph peak discharge q_p per unit drainage area in cubic feet per second (cfs) per square mile per 1 inch of rainfall of duration t_r in hours (t_r=0.18t_p) is (Linsley, et. al., 1982):

$$q_p = \frac{640C_p}{t_p} \tag{2}$$

where C_p is another parameter to be obtained from gaged watersheds and generally ranges from about 0.4 to 0.8.

An acceptable way to derive coefficients C_p and C_t for ungaged streams is to apply Eqs. (1) and (2) to gaged streams in the vicinity. Eqs. (1) and (2) apply to the standard unit hydrograph of duration t_r. For unit hydrographs of other durations (t_R), parameters needed are the excess rainfall duration (t_R) producing the runoff, the basin lag $t_{pR} = t_p$ from Eq. (1), and the unit hydrograph peak discharge $q_{pR} = q_p$ from Eq. (2) of the derived unit hydrograph for the gaged basin using t_{pR} for t_p.

Since q_{pR} is the unit hydrograph discharge per unit area corresponding to unit volume of runoff (excess rainfall) of duration t_R, the peak discharge at the catchment outlet corresponding to a volume R of runoff of duration t_R is:

$$Q_p = q_{pR}RA \tag{3}$$

where A is the catchment area in square miles; R is the runoff amount in inches; and Q_p is the peak discharge at the catchment outlet in cfs.

Q_p at bankfull flow can be related to channel geometrical and roughness characteristics using Manning's equation (Linsley, et. al., 1982); i.e.,

$$Q_p = \frac{1.486A_bR_b^{2/3}S_c^{0.5}}{n} \tag{4}$$

where A_b is the channel cross-sectional area at bankfull conditions in square feet; R_b is the bankfull channel hydraulic depth in feet; S_c is the local channel bottom slope

(dimensionless); and n is Manning's roughness coefficient for bankfull flow.

The cross-sectional channel width (B), and the channel depth (y) are related by a power function ($B=Ky^m$), where K is a scale parameter and m is a shape parameter. This relation can be used to express $A_bR_b^{2/3}$ in Eq. (4) as:

$$A_bR_b^{2/3} = B_b\left(\frac{y_b}{m+1}\right)^{5/3} \tag{5}$$

For any duration (t_R) other than the standard duration (t_r) which Eqs. (1) and (2) assume to be $0.18t_p$, the adjusted lag (t_{pR}) which replaces t_p in Eq. (2) is given by the following expression:

$$t_{pR} = t_p + \frac{t_R - t_r}{4} \tag{6}$$

Solving Eq. (3) for R and substituting from Eqs. (2), (4), (5), and (6) above gives the following expression:

$$R = \frac{0.00232\ B_bS_c^{0.5}}{n\ A\ C_p}\left(\frac{y_b}{m+1}\right)^{5/3}\left[0.955C_t\left(\frac{LL_c}{S^{0.5}}\right)^{0.38} + 0.25t_r\right] \tag{7}$$

where R is the threshold runoff in inches which will cause bankfull flow at the point of interest; B_b is the bankfull width in feet; S_c is the local stream bottom slope in feet per feet; y_b is the bankfull depth in feet; C_t is a coefficient described in Eq. (1); L is the length of stream in miles from point of interest to upstream end; L_c is the length of the stream in miles from the point of interest to the centroid of the area; S is the weighted channel slope throughout the drainage area in feet per mile; t_r is the duration of rainfall in hours; n is Manning's roughness coefficient; A is the drainage area in square miles upstream of the point of interest; C_p is a coefficient described in Eq. (2); and m is the channel shape parameter.

When the parameters to compute Q_p in Eg. (4) are not available from site observations, investigators have found the one- to two-year return period flow, Q_2, as an alternative to computing bankfull flow. (References in Appendix A.) The return period flow is the flow expected to be equalled or exceeded once during the specified time period.

An approach to derive unit hydrographs (unit hydrograph peak, q_{pR}) from basin geometrical characteristics instead of the traditional unit hydrograph derivation has been developed. (Reference in Appendix A.) The geomorphologic unit hydrograph approach does not need "observed" unit hydrographs to estimate the coefficients C_t and C_p in Eqs. 1 and 2, respectively. The unit hydrograph peak, q_{pR}, can be computed without regionalizing parameters and used in Eq. (3) to solve for threshold runoff, R.

The complete mathematical derivation of R and discussion of the values of the parameters in Eq. (7) are given in Appendix A.

6.2 Flash Flood Algorithm

The general rainfall-runoff model equation for computing runoff is:

$$R_t = R_i + R_p \tag{8}$$

where R_t is the total runoff in inches; R_i is the runoff from the impervious area in inches; and R_p is the runoff from the pervious area in inches.

Expanding the terms in Eq. (8) for both the impervious area and the pervious area gives the expression:

$$R_t = P*I + f(P)*(1-I) \tag{9}$$

where P is the precipitation in inches; I is the percent impervious area; and f(P) is the runoff from the pervious area rainfall-runoff model.

For flash flood guidance calculations, P can be renamed as FFG and Eq. (9) rewritten as follows:

$$R_t = FFG*I + f(FFG)*(1-I) \tag{10}$$

where FFG is the flash flood guidance in inches.

In some of the rainfall-runoff models (e.g. Sacramento Model) impervious area is integrated within the model. In other cases, such as with the event API models, impervious area is not a model parameter. In order to apply these API models to urban areas for computing FFG, the impervious area needs to be specified as an additional parameter.

The computation of total runoff R_t above assumes the stream has very little flow compared with the flow at flood stage. At high flows for headwaters and other gaged locations, the additional runoff needed to fill the channel to flood stage is called threshold runoff R_h ($R_h \leq R_t$) and is computed by the following:

$$R_h = \frac{Q_f - Q_i}{q_{pR}} \tag{11}$$

where R_h is the threshold runoff in inches at a high flow; Q_f is the flow in cubic feet per second (cfs) at flood stage; Q_i is the flow in cfs at a time in the future equal to a specified duration; and q_{pR} is the unitgraph peak in cfs.

Q_i in Eq. (11) is set to zero if the adjustment for high base flow is not desired.

For small streams where areal FFG is desired, the total threshold runoff R_t has been determined from channel hydraulics as part of the development effort. To adjust the small stream for high flow, a ratio (C) is applied; i.e.,

$$R_h = R_t(1-C) \tag{12}$$

where R_h is the threshold runoff with the stream at a high flow; R_t is the threshold runoff at low or no flow; and C is the ratio of flow at a time in the future equal to the duration divided by the bankfull flow.

Finally, for headwaters and small streams Eq. (10) is solved for FFG by an iterative process that results in producing the threshold runoff R_t. At a high flow R_h is substituted for R_t in Eq. (10). Then, for headwaters R_h is determined by Eq. (11) and for small streams, Eq. (12).

7. SOFTWARE REQUIREMENTS

New capabilities will require design and development of new software but many of the algorithms are used in current operational software. Several modifications to the existing NWSRFS Operational Forecast System (OFS) will be required that are not described here. The four software packages described below will be used operationally except the first one which will be used non-operationally for development purposes.

7.1 Threshold Runoff

A contractor will design and provide interactive, development software that will use a GIS and DEMs to locate many sub-basin locations on the stream network. After threshold runoffs are computed for these locations, the threshold runoffs are interpolated to the HRAP grid system. A sensitivity analysis conducted by the contractor will determine an optimum scale and size of sub-basins, as well as the extent of variation of the threshold runoff values within river forecast basins.

7.2 FFG Operation for OFS Version 5

A new operation to compute FFG will be added to OFS. The FFG operation will retrieve the snow and soil moisture state variables for the RFC forecast basin. Forecast temperatures and any precipitation since the last state variable update will be included. Using the forecast basin state variables, the snow model and the appropriate rainfall-runoff model will run with several amounts of precipitation to compute the corresponding amounts of runoff that define the rainfall-runoff curve for the basin. A rainfall-runoff curve must be determined for each duration of guidance desired.

An FFG operation will follow the last moisture accounting operation in a segment definition.

The rainfall-runoff curves (one for each duration and each location) are stored in the database for access by the FFG execute program of the flash flood guidance system.

7.3 Flash Flood Guidance Execute Program

This program (not part of OFS) will (1) calculate FFG for each grid bin and (2) merge the rainfall-runoff model estimates of gridded FFG with the intensity estimates.

The gridded FFG is the rainfall needed to produce the gridded threshold runoff. This rainfall is interpolated from the appropriate rainfall-runoff curve at the threshold runoff value. The gridded FFG values are written to the database.

7.4 Message Generation Program

This is an interim program. AWIPS will include the message generation function.

This program (not part of NWSRFS) will retrieve the gridded FFG values from the database and will add an appropriate message heading for transmission to the WFOs. The format of the gridded FFG message must be efficient to handle the large volume of data. SHEF is currently used in hydrology but is presently not designed to handle the large volume of data associated with gridded fields. Gridded meteorological information in AWIPS will use the GRIdded Binary (GRIB) format. Since the WFOs will have GRIB decoders, gridded FFG will be sent in GRIB.

The message generation program will also retrieve areal FFG values from the database in a specified sequence and add an appropriate message heading for transmission of public forecast zone, county, and urban guidance products in SHEF to the WFOs. Thus, an RFC could convert to the new FFG operation in NWSRFS before AWIPS and continue its current flash flood guidance products in SHEF.

8. RESOURCES

Modernization has high priority. The National Flash Flood Program Leader, Hydrologic Services Branch, has the lead in the FFG project for design, development, and documentation. The Hydrologic Research Laboratory will provide the technical expertise for determining threshold runoff values and integrating FFG in OFS Version 5. A contractor will provide the development software and documentation for deriving threshold runoff. Several personnel from field offices are participants in the effort to assure that needs will be met with the centrally supported FFG package.

9. TEST AND EVALUATION

Test and evaluation must examine both threshold runoff and FFG. This is the first effort to implement uniform methodology in producing FFG in the NWS. Ideally, site vists to numerous locations on small streams to measure bankfull widths and depths and to determine the shapes of the streams and stream slopes (from topographic maps) would provide the information to compute threshold runoffs. Since a year or two would be required to collect this information with current resources, another course of action is necessary. The concept of deriving threshold runoff from digital elevation databases and GIS is new to NWS. This is new technology and some research into this approach, as well as the methodology, was appropriately assigned to a contractor. A reasonable approach is to integrate basic hydrologic concepts

with the newer DEM and GIS technology. Hydrology is not exact; a number of assumptions are made in the derivation of the threshold runoff and the synthetic hydrograph approach. As resources become available for site surveys as needed, the emerging methodology can use actual site observations instead of digital elevation databases.

Threshold runoffs will be compared with current values. If current values produce useable FFG, then gridded threshold runoffs must be close to the current values. Gridded values in a county or zone should cover a range of values unlike current threshold runoffs that are averages for the county or zone. Assuming that gridded threshold runoffs are valid, gridded FFG values in a county or zone, likewise should range below and above current values for the county or zone.

Some interest has been expressed for 2 km gridded FFG. Both FFG and radar would be more useful on a 2 km grid to detect the small scale rain events experienced in various parts of the country. Radar data is available graphically on a 2 km grid but the high noise level in the data makes it unuseable. The 2 km data is not available in digital form for use with applications. When these matters are resolved in the future and with digital elevation data of sufficient resolution, FFG could be provided on a 2 km grid.

Field testing of the FFG system will be done at the Tulsa RFC as part of the Tulsa-Norman risk-reduction activity. To further test the usage and application of the new FFG, it would also be advantageous to run the software in different and varying RFC environments. Only an RFC that runs NWSRFS on a PRIME mini-computer could utilize some of the FFG system but unless the RFC has an AWIPS configured WFO, gridded FFG can not be used. The FFG system is intended for the AWIPS RFC offices.

10. FUTURE IMPROVEMENTS

A future model development effort after the Modernization and Associated Restructuring Demonstration (MARD) could include a gridded moisture accounting model and redefining sub-basin soil moisture accounting parameters based on local (grid) land use and soil type databases. This change would allow separate soil moisture accounting on unique local soil features. Some software changes are anticipated. Phase 2 (Figure 1c) shows the gridded model with the land use and soil type feature. The gridded model may be a separate program but it needs to access the RFC's current forecast model to keep on track; i.e., after a few days with no rain the gridded soil moisture accounting model would be re-initialized with the current RFC basin-wide values.

11. ACKNOWLEDGEMENTS

Modernized FFG is a cooperative effort in NWS by participants from many offices. Operational capabilities and features in the flash flood guidance package were specified by the RFCs and regional hydrologists. Technical and development strategy was coordinated with the Hydrologic Research Laboratory; namely, Dr. Danny Fread for deriving the basic threshold runoff equation and Dr. Eric Anderson for integrating flash flood guidance in NWSRFS.

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Appendix A

DERIVATION OF THRESHOLD RUNOFF

The approach used to determine threshold runoff values used for computing flash flood guidance (FFG) for small streams is presented in the following discussion.

For a standard unit hydrograph of duration t_r, Snyder found the basin lag to be a function of basin size and shape (Chow, et. al., 1988). A more general form for this relation (Linsley, et.al., 1982) is given by the following:

$$t_p = C_t\left(\frac{LL_c}{\sqrt{S}}\right)^b \tag{1}$$

where t_p is the basin lag in hours, defined as the time from the centroid of rainfall to the peak of the unit hydrograph; C_t is the coefficient to be derived from gaged watersheds in the same region (generally varies from 0.3 to 1.2); L is the stream distance in miles from the outlet to the basin boundary, L_c is the stream distance in miles from the outlet to the point on the stream nearest the catchment centroid; S is the watershed channel slope in feet per mile; and b is a constant assumed to be 0.38 (Linsley, et.al., 1982).

The peak discharge q_p per unit drainage area in cubic feet per second (cfs) for a duration (t_r) is the following:

$$q_p = \frac{640C_p}{t_p} \tag{2}$$

where C_p is another parameter to be obtained from gaged watersheds and ranges from about 0.4 to 0.8.

Coefficients C_p and C_t for ungaged streams can be derived by application of Eqs. (1) and (2) to gaged streams in the vicinity.

<u>Coefficient C_t</u>

A simple calibration method, derived from Eq. (1), for determining C_t is the following:

$$C_t = \frac{T_p - t_r/2}{\left(\frac{LL_c}{\sqrt{S}}\right)^{0.38}} \tag{3}$$

where T_p is the time of rise, hours.

The C_t for a region is the average of the C_t for each basin in the region.

If unitgraphs are not available for several parts of the U.S. to determine C_t, use the values given for various terrain as defined following Eq. (1) in the main text.

Coefficient C_p

Solving Eq. (2) for the coefficient C_p gives the following relation:

$$C_p = \frac{q_p t_p}{640} \tag{4}$$

If q_{pR} is the unit hydrograph peak discharge per unit area corresponding to unit volume of runoff of duration t_R, the total discharge at the outlet corresponding to a volume R of runoff is given by the following:

$$Q_p = q_{pR} RA \tag{5}$$

Then, since $q_{pR}=Q_p/RA$, substituting this for q_p into Eq. (4) gives the following relation for C_p:

$$C_p = \frac{Q_p t_p}{640\ R\ A} \tag{6}$$

where Q_p is the total discharge in cfs; t_p is the basin lag in hours; R is the runoff in inches; and A is the basin area in square miles.

The C_p for a region is the average of the C_p for each basin in the region.

Threshold Runoff

After estimates are obtained for C_t and C_p for a region, Eq. (5) can be solved for runoff (R) as follows:

$$R = \frac{Q_p}{q_{pR} A} \tag{7}$$

Before solving Eq. (7), expressions for the variables (Q_p) and (q_{pR}) are derived in the following manner. Q_p at bankfull flow can be related to channel geometrical and roughness characteristics using Manning's equation (Linsley, et. al., 1982); i.e.,

$$Q_p = \frac{1.486 A_b R_b^{2/3} S_c^{0.5}}{n} \tag{8}$$

where A_b is the channel cross-sectional area in square feet at bankfull; R_b is the channel hydraulic radius in feet at bankfull; S_c is the local channel bottom slope (dimensionless); and n is the Manning's roughness coefficient.

For bankfull discharge the hydraulic radius (R_b) can be expressed as follows:

$$R_b = \frac{A_b}{P_b} \tag{9}$$

where P_b is the wetted perimeter. However, for most rivers P_b is sufficiently approximated by the bankfull width (B_b). Thus, P_b in Eq. (9) can be replaced by B_b to obtain the following expression for R_b:

$$R_b = \frac{A_b}{B_b} = D_b \tag{10}$$

where D_b is the bankfull hydraulic depth. Upon substituting Eq. (10) into Eq. (8), Manning's equation takes the following form:

$$Q_p = \frac{1.486 A_b D_b^{2/3} S_c^{0.5}}{n} \tag{11}$$

If the cross-sectional channel width (B) and the channel depth (y) are related by a power function; i.e.,

$$B = Ky^m \tag{12}$$

where K is a scale parameter and the power (m) represents the shape parameter of the cross-section. Values for m range from 0 for rectangular, 0.2 for bowl-shaped, 0.5 for parabolic, 1.0 for triangular, and to 1.5 for triangular with convex-shaped banks.

Integrating Eq. (12) with respect to the depth (y) gives the cross-sectional area (A), and using A_b and y_b to represent bankfull conditions gives:

$$A_b = K\frac{y_b^{m+1}}{m+1} \tag{13}$$

Since the cross-sectional area (A_b) can be expressed as $D_b \cdot B_b$, then

$$D_b = \frac{A_b}{B_b} = \frac{K\ y_b^{m+1}}{(m+1)Ky_b^m} = \frac{y_b}{m+1} \tag{14}$$

Substituting the results of Eq. (14) for the term $A_bD_b^{2/3}$ in Eq. (11) gives the following expression:

$$A_bD_b^{2/3} = D_bB_bD_b^{2/3} = B_bD_b^{5/3} = B_b\left(\frac{y_b}{m+1}\right)^{5/3} \tag{15}$$

Upon substituting this expression for $A_bD_b^{2/3}$ into Eq. (11) gives the following:

$$Q_p = \frac{1.486S^{0.5}B_b}{n}\left(\frac{y_b}{m+1}\right)^{5/3} \tag{16}$$

The peak discharge (q_{pR}) of the unit hydrograph for a runoff (excess rainfall) of any other duration (t_R) can be computed by first adjusting Eqs. (1) and (2) for the standard duration (t_r). For any other duration (t_R), the adjusted basin lag (t_{pR}) (Linsley, et. al., 1982) is:

$$t_{pR} = t_p + (t_R - t_r)/4 \tag{17}$$

Snyder (Chow, et. al., 1988) found that $t_r = t_p/5.5$ and substituting this for t_r into the Eq. (17) gives the following:

$$t_{pR} = 0.955t_p + 0.25t_r \tag{18}$$

Then substituting Eq. (18) into Eq. (2) for t_p gives the unit hydrograph peak for a duration of t_{pR} as follows:

$$q_{pR} = \frac{640C_p}{0.955t_p + 0.25t_r} \tag{19}$$

Substituting Eq. (1) for t_p in Eq. (19) gives the following expression for q_{pR}:

$$q_{pR} = \frac{640c_p}{0.955C_t\left(\frac{LL_c}{S^{0.5}}\right)^{0.38} + 0.25t_r} \tag{20}$$

Now that relations to compute the variables (Q_p) via Eq. (16) and (q_{pR}) via Eq. (20), Eq. (7) can be expressed in the following form:

$$R = \frac{0.00232 B_b S_c^{0.5}}{nAC_p}\left(\frac{y_b}{m+1}\right)^{5/3}\left(0.955C_t\left(\frac{LL_c}{S^{0.5}}\right)^{0.38} + 0.25t_r\right) \qquad (21)$$

The variables and their sources are:

R - threshold runoff (inches)

From observation of rainfall events:
t_r - duration of rainfall (hr)

From analysis of gaged streams in region:
C_p - coefficient (generally ranges from about 0.4 to 0.8)
C_t - coefficient (generally ranges from about 0.3 to 1.2)

From site inspection:
B_b - bankfull width (ft)
y_b - bankfull depth (ft)
m - channel shape factor (0=rectangular, 0.2=bowl-shaped, 0.5=parabolic, 1.0=triangular, 1.5=triangular with convex-shaped banks)

From site inspection, estimation, or calibration:
n - Manning's n, range 0.035 to 0.15. The Manning roughness coefficient (n) for bankfull flows can be computed (Jarrett, 1987) from the expression:

$$n = \frac{0.39 S_c^{0.38}}{\left(\frac{y_b}{m+1}\right)^{0.16}} \qquad (22)$$

subject to $n \geq 0.035$.

From map derived (GIS and DEM):
S_c - local stream bottom slope (ft/mi)
S - weighted channel slope in drainage area (ft/mi)
A - drainage area (sq mi) upstream of point of interest
L - length (mi) of stream from point of interest to the stream's uppermost end
L_c - length (mi) of stream from point of interest to the centroid of the drainage area above the point.

A Geographical Information System (GIS) and Digital Elevation Model (DEM) can aid in the determination of y_b, B_b, and m. From site inspections at several locations on small streams, values for y_b and B_b can be determined. Then, regression equations can be developed, using the observed values from the

site inspections along with drainage area size and slope to derive similar parameters for other small streams in the vicinity.

Two Year Return Period Flow

When the parameters to compute Q_p in Eq. (7) are not available from site observations (i.e., B_b, y_b, and m in Eq. (16)), investigators have found the one- to two-year return period flow, Q_2, as an alternative to computing bankfull flow, Q_p, (Riggs, 1990). The return period flow is the flow expected to be equalled or exceeded once during the specified time period. For bankfull flow the return period varies around 1.5 years but the two-year return period more closely approximates when minor flooding begins at slightly over bankfull.

Geomorphologic Unit Hydrograph

An approach to derive unit hydrographs that avoids the need for "observed" unit hydrographs for peak flow (q_{pR}) requires geometrical catchment characteristics obtainable from GIS software and digital terrain elevation databases. The approach avoids the need for estimating regionalized coefficients C_t and C_p in Eqs. (3) and (6), respectively, to solve Eq. (20) for q_{pR} for use in Eq. (7). The approach is described in papers by Rodriguez-Iturbe, et al., (1979 and 1982). The characteristics are properties of the links formed by the channel network within the catchment when it is ordered according to Strhaler's ordering scheme and using Horton's geomorphological laws (Eagleson, 1970). Using kinematic wave analysis and channel geometrical characteristics, i.e. bankfull width (B_b), local channel slope (S_c), and Manning's roughness coefficient (n), the time to peak (t_p) can be expressed as

$$t_p = C_3 \Pi^{0.4} \tag{23}$$

and the peak value, q_{pR}, as

$$q_{pR} = \frac{C_4}{\Pi^{0.4}} \tag{24}$$

and

$$\Pi = \frac{L^{2.5}}{iAR_L \left(\frac{S_c^{0.5}}{n\ B_b^{2/3}} \right)^{1.5}} \tag{25}$$

where the variables are:

- C_3 - coefficient depending on the system of units used (0.576 for English units)
- C_4 - coefficient depending on the system of units used (0.884 for English units)
- L - length (mi) of stream from point of interest to the stream's uppermost end
- i - rainfall intensity (in/hr)
- A - drainage area (sq mi) upstream of point of interest
- R_L - stream length ratio (A property of the stream network relating the mean stream length to Strhaler's stream order. Eagleson (1970) or Bras (1990) review the geomorphological laws in their texts.)
- S_c - local channel slope (ft/mi)
- n - Mannings's roughness coefficient from Eq. (22)
- B_b - bankfull width (ft) from a bankfull width vs drainage area regional relationship or local regression equation derived from site observations of B_b and GIS measurement of drainage area and channel slope.

This is still an active area of research but the approach is an alternative to the synthetic unit hydrograph method.

The two year return period flow and the geomorphologic unit hydrograph are attractive approaches in computing the threshold runoff. The methodology can be applied to all regions of the country. Initial values for Mannings's roughness coefficient can be computed from Eq. (22), and for bankfull width, from bankfull width vs. drainage area relationship or regional regression equations. However, such a method does not negate the need for "observed" parameters and unit hydrographs. When locally observed information is available, n and B_b in Eq. (25) should be optimized within certain limits, i.e., n should be limited to values between 0.02 to 0.09, and B_b should be limited to a range of one half to twice the initial value.

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Appendix B

HEADWATER FLASH FLOOD GUIDANCE

Threshold Runoff

For headwater guidance, threshold runoff is the flow at flood stage divided by the unitgraph peak for a certain duration.

FFG Operation

The FFG operation would generate a rainfall-runoff curve for each river forecast basin where headwater flash flood guidance is desired. Using the river forecast basin state variables of the models and forecast temperatures (if snow is included), several rainfall and corresponding runoff values would be computed to define the rainfall-runoff curve for each river forecast basin. Curves for 1-, 3-, and 6-hour duration would be computed and written to the database. The FFG operation would only be executed when a guidance run was specified. Operations after the FFG operation would be skipped and only the rainfall-runoff curves would be written to the database. Only one FFG operation is needed for a river forecast basin when both areal and headwater flash flood guidance is desired.

Snowmelt, frozen ground, and other new features would be included as discussed earlier for areal FFG.

FFG Execution Program

The FFG execute program will calculate the headwater guidance for each duration. Guidance values are interpolated from the rainfall-runoff curves (from the FFG operation in NWSRFS) at the threshold runoff values. The headwater FFG values are written to the database.

Message Generation Program

This program will generate headwater guidance products in SHEF by accessing the database in a specified sequence for the FFG values produced by the FFG execute program. Thus, before AWIPS arrives an RFC could continue to issue its current headwater flash flood guidance products in SHEF by implementing the FFG operation in NWSRFS and converting its FFG software.

(Continued from inside front cover)

NWS HYDRO	18	Numerical Properties of Implicit Four-Point Finite Difference Equations of Unsteady Flow. D. L. Fread, March 1974, 38 pp. (COM-74-011691)
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NWS HYDRO	20	Storm Tide Frequency Analysis for the Gulf Coast of Florida from Cap San Blas to St. Petersburg Beach. Francis P. Ho and Robert J. Tracey, April 1975, 34 pp. (COM-75-10901/AS)
NWS HYDRO	21	Storm Tide Frequency Analysis for the Cost of North Carolina, South of Cape Lookout. Francis P. Ho and Robert J. Tracey, May 1975, 44 pp. (COM-75-11000/AS)
NWS HYDRO	22	Annotated Bibliography of NOAA Publications of Hydrometeorological Interest. John F. Miller, May 1975, 50 pp. (Superseded by NWS HYDRO 34)
NWS HYDRO	23	Storm Tide Frequency Analysis for the Coast of Puerto Rico. Francis P. Ho, May 1975, 43 pp. (COM-11001/AS)
NWS HYDRO	24	The Flood of April 1974 in Southern Mississippi and Southeastern Louisiana. Edwin H. Chin, August 1975, 45 pp. (COM-75-11387/AS)
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