6B.2   **SPATIALLY-VARIABLE, PHYSICALLY-DERIVED FLASH FLOOD GUIDANCE**

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1. Introduction

The National Weather Service (NWS) flash flood program can be traced back to the Independence Day, 1969 flood event in the coastal counties of Ohio. Forty-one deaths and 559 injuries were recorded in Ohio as a result of this flooding and severe weather. In response to this event, NWS River Forecast Centers (RFCs) began producing flash flood guidance (FFG) values of different spatial and temporal extent to support the local Weather Forecast Office's (WFO) flash flood warning mission. The methods and models used to produce these FFG values varied between RFCs.

In the late 1980s, the NWS's Hydrologic Research Lab began developing the NWS modernized FFG system (Sweeney, 1992). This new method of producing FFG utilized the uniform NWS River Forecast System (NWSRFS) that had been developed and deployed at RFCs during the previous two decades. This system allowed for the generation of county, basin, headwater and gridded FFG values based on the underlying NWSRFS hydrologic model. The gridded FFG produced by this system was "gridded" in name only. It was simply the transformation of the larger, basin-averaged FFG value to the Hydrologic Rainfall Analysis Project (HRAP) grid (Fulton et al, 1998). Most, if not all, WFOs continued to use the spatially- averaged FFG in their flash flood warning operations.

In the early 2000s, the Flash Flood Monitoring and Prediction (FFMP) software was developed for use at WFOs to aid in the accumulation of radar estimates of rainfall and to compare those accumulations (by ratio or difference) to a FFG value. FFMP is "an outgrowth and merging of existing capabilities within the WFO Hydrologic Forecast System (WHFS) HydroView application and the System for Convection Analysis and Nowcasting (SCAN)" (Smith et al, 2000), as well as Pittsburgh WFO's Areal Mean Basin Estimated

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Rainfall (AMBER) methodology. WFOs now have the capability to assess rainfall accumulations on flash-flood scale basins that are described by a wide variety of topographic, geomorphologic and other physical characteristics. Unfortunately, the FFG values that are being used for comparison and warning decision-making are still based on a lumped-parameter, conceptual model, at a scale of nearly 200 FFMP basins to the average Arkansas-Red Basin River Forecast Center (ABRFC) lumped-parameter basin (Figure 1).
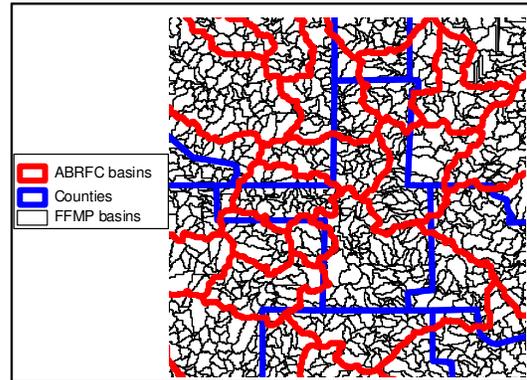
Figure 1: Tulsa County, OK overlaid with ABRFC-model scale basins and FFMP scale basins.

To gain full benefit from the use of FFMP in flash flood warning operations, the ABRFC has developed a soil-moisture accounting, gridded, flash-flood guidance (GFFG) model that reflects the variable physical properties of FFMP basins. The ABRFC's GFFG mimics the existing architecture of the NWS's modernized FFG model described by Sweeney (1992), but employs a distributed hydrologic model to account for soil moisture changes, the Natural Resource Conservation Service's (NRCS) Curve Number Model to account for the variety of physical characteristics and the NRCS Unit Hydrograph Model combined with a design storm to estimate bankfull flow. The GFFG model is run on the HRAP grid. This grid resolution, approximately 4km x 4km, is more consistent with the spatial scale of the FFMP basins and therefore allows the model to treat

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each HRAP grid cell as an independent headwater basin.

2. ABRFC's Gridded Flash Flood Guidance (GFFG) Model Description.

The GFFG Model can be divided into three major components: a distributed hydrologic model to perform soil moisture accounting, a rainfall/runoff model to predict runoff potential and a static model to estimate a critical runoff threshold.

ESRI's ArcView Version 3.1 and Spatial Analyst Extension were used extensively in the development of the GFFG model. While numerous data sets from several different organizations were used in evaluating different models and methodologies, only the following gridded data are required to produce the current GFFG product:

1. Hourly estimates of precipitation (ABRFC),
2. National Land Cover Data (NLCD) (United States Geological Survey (USGS)),
3. State Soil Geographic (STATSGO) hydrologic soil group (NRCS via Pennsylvania State University),
4. Hillslope (NWS/OHD)
5. Sacramento Soil Moisture Accounting gridded a priori model parameters (NWS/OHD),
6. Oklahoma 5-year, 3-hour depth, duration, frequency precipitation data (USGS),
7. Parameter-elevation Regressions on Independent Slopes Model (PRISM) annual precipitation climatology 1971-2000 (Oregon Climate Service).

2.1 NWS Hydrology Laboratory Research Modeling System (HL-RMS)

The initial test of the GFFG model employed an antecedent precipitation index (API) model to perform the soil moisture accounting function. After consultation with the NWS Office of Hydrology, the HL-RMS was tested to fulfill this function since it modeled hydrologic processes independently instead of through a constant loss parameter. The more robust HL-RMS model was found to provide superior soil moisture estimates without undue computational overhead.

The HL-RMS allows the user to run in an "unconnected" mode, only performing the water balance component and omitting the hillslope and channel routing components. The HL-RMS model outputs the model parameter grids required for subsequent model runs, providing a continuous simulation. The two output parameters the GFFG model requires are the Sacramento Soil Moisture Accounting Model's Upper Zone Tension Water Contents (UZTWC) and Upper Zone Free Water Contents (UZFWC). The maximum possible sizes of each of these parameters, UZTWM and UZFWM, respectively, are estimated using physical relationships described by Koren et al (2000).

After each HL-RMS run, the UZTWC and UZFWC grids are added together and divided by the sum of their potential maximum values of UZTWM and UZFWM to produce a gridded, upper-zone saturation ratio value.

2.2 NRCS Curve Number Model

The NRCS Curve Number (CN) model has a long history of varied applications and misapplications (Hjemfelt et al, 2001). The attractiveness of the CN model lies in its simplicity and physical basis. NLCD land use-land cover (LULC) (Figure 2) and STATSGO hydrologic soil group (HSG) (Figure 3) data are compared via a lookup table (Appendix A) to estimate CN values (Figure 4).
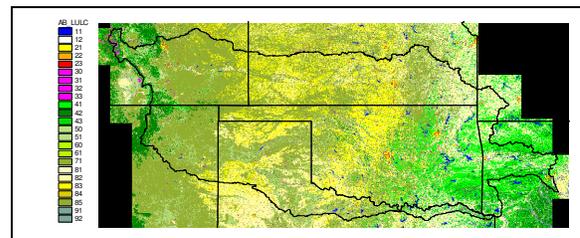

Figure 2: NLCD Land Use Land Cover Classification System.
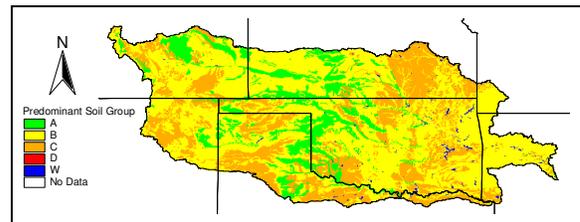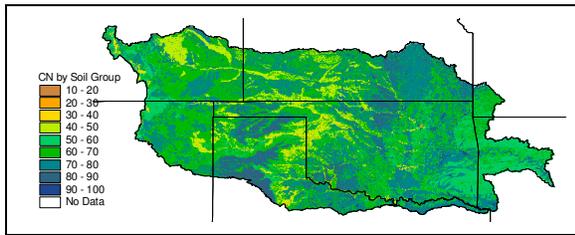

Figure 3: Hydrologic Soil Groups.

Generally, the more urban, clayey soil parcels receive high CNs, while the more rural, sandy soil parcels are assigned lower CNs. The

higher the CN, the more runoff is produced for a given rainfall event. Lower CNs reflect lower runoff producing potential.

Figure 4: ARC II Curve Number Estimates from LULC and HSG data.

The NRCS CN model also allows for the accounting of antecedent soil moisture states by analyzing the past five day's rainfall totals and the time of year of the model run. This method of soil moisture accounting has been replaced in the GFFG model by using the saturation ratio value calculated for each grid cell as described in section 2.1. The "wet" and "dry" equations employed by the CN method are used as bounds for the HL-RMS's upper zone 100 percent saturation and zero percent saturation, respectively, and are calculated using:

$$CN_{ARCI} = \frac{4.2 * CN}{10 - 0.058 * CN};$$ (1)

and

$$CN_{ARCIII} = \frac{23 * CN}{10 + 0.13 * CN};$$ (2)

where *ARCI* and *ARCIII* are defined as the dry and wet antecedent rainfall condition, respectively, and *CN* denotes the "normal" curve number.

The "normal" soil moisture ratio was defined to be 50-percent saturation and values were linearly interpolated between the three curves for the intermediate "percent saturation" values (Equations 10 and 11). This method is graphically depicted in Figure 5. Given an ARCII CN of about 60, and completely saturated upper soil zones (ARC=III), the soil-moisture adjusted CN would be about 80.
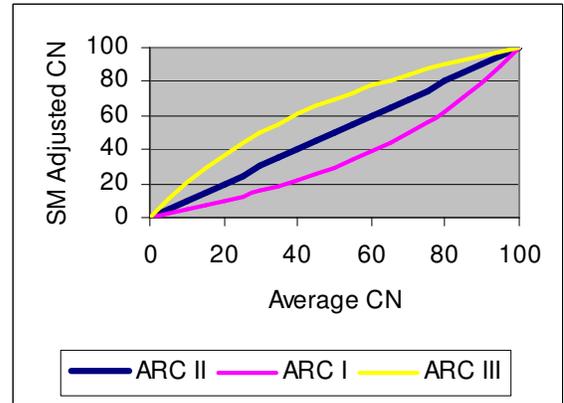
Figure 5: Curve Number (CN) adjustment based on antecedent soil moisture (SM) condition.

The final step of the CN model is to calculate available upper zone rainfall storage given an antecedent soil-moisture adjusted CN using the relationship:

$$S_{sm} = \frac{1000}{CN_{sm}} - 10;$$ (3)

where S_{sm} is defined as initial abstraction for interpolated soil moisture CN.

2.3 Threshold Runoff (ThreshR)

ThreshR can be generically defined as the amount of runoff required to exceed some critical level. It is calculated by dividing the critical flow, Q_s, by the peak of the drainage area's unit hydrograph, Q_p.

Historically, the NWS has considered that critical level to be bankfull flow on interior streams. Several methods were screened to estimate "bankfull flow" across the ABRFC domain: 1) calculated 2-year return flow based on USGS regional regression equations (Reed et al, 2002), 2) calculated bankfull flow using regression equations based on a wide variety of different groupings and variables in Oklahoma (Dutnell, 2000) and 3) a technique derived from a methodology of estimating channel shape parameters using streamflow measurements in distributed hydrologic routing (Reed, Koren et al, 2002). These methods were successful to a lesser or greater extent across portions of the ABRFC domain, but none of them was successfully applied to the ABRFC area in its entirety.

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Instead of using 2-year return flow values as estimates of bankfull flow, a 5-year, 3-hour, design rainfall event was used as the precipitation input to the NRCS Curve Number Model. Since 5-year, 3-hour design events did not exist in a digital format for all the constituent states of the ABRFC area, PRISM annual rainfall grids were regressed against the Oklahoma 5-year, 3-hour gridded data with good correlation (R^2=0.8). This relationship was applied across the entire ABRFC basin producing a basin-wide estimate of the 5-year, 3-hour design storm, as illustrated in Figure 6. The resultant runoff amount was time distributed using the NRCS Triangular Unit Hydrograph Method and the peak flow was selected as Q_s.
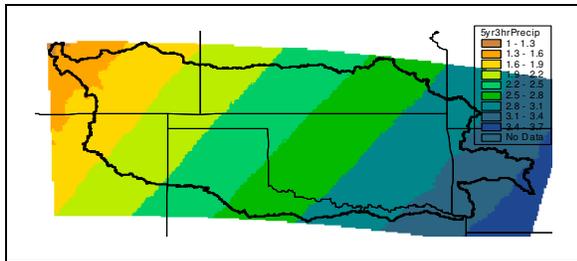
Figure 6: Estimated 5-year, 3-hour design precipitation event ranging from 3.2cm in the Colorado Rockies to 9cm near Little Rock, AR.

The peak flow value, Q_p, was generated by calculating a unit event of a given duration. The NRCS Triangular Unit Hydrograph Method was employed to calculate Q_p because of its simplicity and inclusion of slope as a variable, and is calculated through the following series of equations:

$$t_p = \frac{l^{0.8}(S+1)^{0.7}}{1900y^{0.5}} \; ; \tag{4}$$

where: t_p = lag time (hr),
l = length to divide (ft),
y = average watershed slope (%),
S = available storage from CN.

$$T_R = \frac{D}{2} + t_p \; ; \tag{5}$$

where: T_R = time of rise (hr),
D = rainfall duration (hr),
T_p = lag time from centroid of rainfall to Q_p (hr).

$$Q_p = \frac{484A}{T_R} \; ; \tag{6}$$

where: Q_p = peak flow (cfs),
A = area of basin (sq mi),
T_R = time of rise (hr).

ThreshRs for different durations are generated by changing the D variable in the T_R equation (Equation 5). Additionally, the abstraction value, S, used in Equation 3 must be modified to account for the variability in event duration. Four inches of precipitation in one hour will generally produce more runoff than four inches of precipitation in six hours. To accommodate this reality the curve numbers used to calculate 1-hour ThreshR values are estimated to be an average of the ARCIII and ARCII values and the 6-hour ThreshR values are estimated using an average of the ARCI and ARCII values.

The average range of gridded ThreshR values produced using this method was similar to the average range of basin-averaged legacy values, but the new values logically followed landforms. That is, ThreshR values were generally lower in areas of heavy relief and higher in areas of little relief (Figures 7 and 8). It is important to note that these ThreshR values use an estimate of bankfull flows on a gridded scale and may or may not reflect the level at which flash flooding problems occur.

Figure 7: Legacy 3-hour ThreshR values ranging from .33 cm in Colorado to 2.54 cm in Arkansas.

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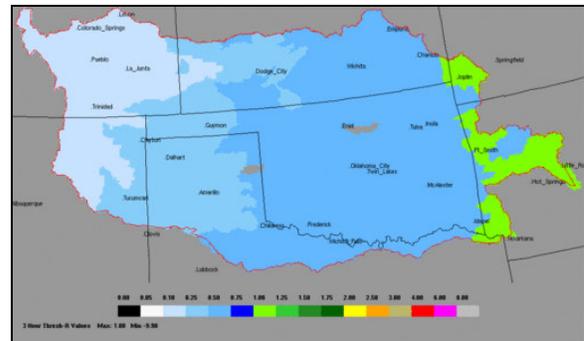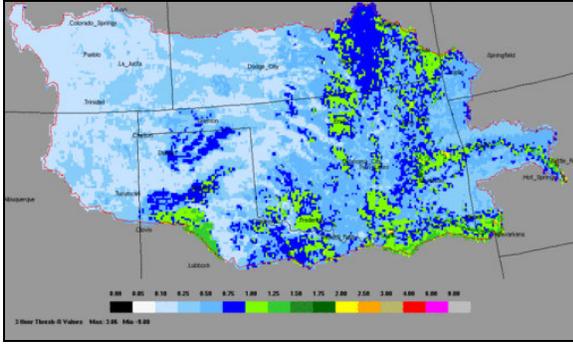
Figure 8: Gridded 3-hour ThreshR values ranging from 0.50 cm to some isolated 2.00 inches.

2.4 *Calculating Gridded Flash Flood Guidance (GFFG)*

Traditionally, the CN method is used to calculate runoff for a given S_{sm} and precipitation amount using:

$$Q = \frac{(P - 0.2S_{sm})^2}{P + 0.8S_{sm}} ; \qquad (7)$$

where: Q = runoff (in),
P = precipitation (in),
S_{sm} = initial abstraction calculated from equation 3.

However, FFG represents the precipitation required to produce a given runoff value, ThreshR. Therefore, equation 7 is solved for P, the FFG value:

$$P = \frac{0.2S_{sm} + Q_x \pm \sqrt{2Q_x S_{sm} + Q_x^2}}{2} ,$$

$$P = FFG_x ; \qquad (8)$$

where: FFG_x = rainfall in x hours required for flash flooding to begin,
S_{sm} = initial storage calculated from equation 3,
Q_x = threshold runoff for x hours.

3. Calibration, Validation and Verification

The ABRFC GFFG model is a compilation of well-heeled and new techniques and models combined to replicate the existing NWSRFS FFG architecture on a gridded scale. The initial goal of GFFG was to produce FFG values that are similar to the legacy FFG at the basin scale, but at a more precise resolution for use in FFMP. Calibration of the model and validation of assumptions made were accomplished through averaging the gridded ThreshR and GFFG values up to the basin or county scale and comparing them to the legacy values. It appears that this is generally the case in evaluating a variety of different days' plots of basin-averaged GFFG against lumped-parameter FFG. Figure 9 is a typical representation of basin-averaged GFFG values plotted against the legacy, basin-averaged FFG values.
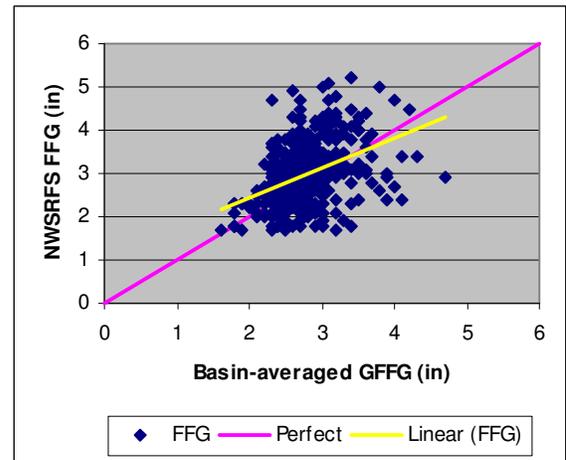
Figure 9: September 18, 2006 Basin-Averaged GFFG versus NWSRFS Basin FFG.

While this method of "verification" indicates there is some validity to the GFFG assumptions and models, it assumes that the legacy, basin-averaged FFG values are valid. This may be a poor assumption as, at this time, "no verification system exists to provide feedback on the accuracy of the FFG RFCs provide to WFOs." (RFC Development Management Team, 2003)

The ABRFC attempted to devise a system to allow WFOs to evaluate the GFFG product parallel to the legacy, operational FFG product. This proved to be too cumbersome. Some frank comments on the lack of operational utility of the legacy, gridded FFG product led to an ABRFC/WFO consensus decision to replace it with the GFFG product. This allowed for operational use, feedback and verification from the primary user group of FFG, the WFOs.

In an effort to assist the WFOs in their GFFG and flash flood warning verification efforts, the ABRFC developed an application to compare 1, 3 and 6-hour accumulations of

ABRFC gridded, gage-adjusted, radar estimates of precipitation to the valid 1, 3 and 6-hour GFFG values. Output of this application includes a binary map indicating which grid cell's GFFG values were exceeded in the previous 24 hours. Users can drill down to their specific WFO area to determine which duration of GFFG was exceeded and by how much. In limited use, this tool has proved useful.

Over the past ten years, much of the "improvement" to the legacy FFG values has been the resolution of RFC-to-RFC boundary inconsistencies. This was especially beneficial to those WFOs that were served by more than one RFC. The result of that RFC-to-RFC collaboration can be seen in Figure 10 in Appendix B. It is difficult to distinguish the boundaries of the six different RFCs that are partial or complete contributors to the region depicted in Figure 10. There was a concern that the implementation of a completely new set of hydrologic models and calculations of ThreshR only in ABRFC's area would result in discontinuities along adjoining RFCs. Figure 11 in Appendix B shows that while the data itself appears significantly different, the border areas with neighboring RFCs have relatively good fit.

4. Operational Production of GFFG

GFFG products are produced 3 times daily during normal operating hours, closely following the 12Z, 18Z and 00Z hours. Products will non-routinely be issued at 06Z during times of extended ABRFC staffing or intermittently during the day when significant changes have been made to the hourly precipitation estimates that drive the HL-RMS.

One, three and six-hour gridded flash flood guidance and the county averages of those three durations are produced through the execution of a single UNIX script. Several additional scripts and programs have been written to incorporate the GFFG model into the existing operational RFC environment. As a result, the production of GFFG requires no additional operational duties for the ABRFC forecasters.

A general description of the GFFG production follows. After the latest hourly precipitation products have been produced, the HL-RMS model is run. At the completion of this run, the gridded upper zone saturation ratio field and the resultant curve number grid are calculated using a C program. The remainder of this program calculates the current, soil-moisture

adjusted GFFG grid for the 1, 3 and 6-hour durations. These three grids are then copied into the existing legacy NWSRFS FFG file architecture, where the old basin-averaged grid resides. The NWSRFS FFG program is then used to calculate county-averaged FFG values based on the GFFG products and transmit text and gridded products to the WFOs. The only operational difference the WFO notices is that the new GFFG product depicts spatial differences in soil moisture, slope, soil quality, land use and climatology. Appendix C graphically illustrates the difference between the legacy FFG system and the GFFG values, especially in the highlighted basin in the center of the panes. Appendix B shows the difference on a much broader scale.

The GFFG model was initialized in December, 2005 and allowed to run unmodified until its operational deployment on August 30, 2006. While precipitation inputs are updated on a regular cycle and modeling techniques may be replaced, no run-time adjustments are made to the model. No long-term, biased drifting of the GFFG values has been noted.

5. Conclusions

Several different models, methods and utilities are under investigation and development at this time to improve the quality and success of flash flood warnings at NWS WFOs, all with the ultimate goal of saving more lives and property. Each has its strengths and weaknesses.

The primary strength of the ABRFC GFFG model is the much finer spatial scale of its calculations when compared to the basin-averaged legacy NWSRFS FFG system. That is, it uses gridded precipitation estimates to drive a distributed hydrologic model to perform soil moisture accounting on the same 4km x 4km grid and uses gridded, physical datasets to model the susceptibility of a small basin to rapidly produce and accumulate runoff. A secondary, but often overlooked, strength is the ability to seamlessly integrate the ABRFC GFFG products into the existing flash flood warning environment currently in place at the WFOs. The flash flood warning forecaster should be able to use a similar mindset in analyzing an evolving flash flood threat as with the legacy FFG products. However, when using GFFG as an input to FFMP, he can more confidently evaluate the flash flood threat at a smaller spatial scale, and provide more accurate and specific flash flood warnings.

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It is apparent that accounting for local distributions of precipitation and subsequent soil moisture is essential to small-scale flash flood warning in ABRFC's area. Perhaps an improvement of equal importance could be realized in moving from an estimate of ThreshR to a measured, site-specific ThreshR. While this is not realistic for every grid cell or FFMP basin, it would provide improved GFFG values at high risk or frequently-flooded locations.

6. Future Work

While GFFG is a significant improvement over the legacy FFG system when used in concert with FFMP, it is still a raw project and has much room for improvement.

Currently, *depth-to-bedrock* is not accounted for in the model. This results in artificially high GFFG values in the Rocky Mountains of Colorado and New Mexico, where highly permeable but shallow soils exist. This will be an important improvement that should allow for broader applicability in areas that are not as sensitive to antecedent soil moisture, such as most of the Rocky Mountain region.

The ABRFC basin does have a variety of climate regimes, from the semi-arid eastern slopes of Colorado and New Mexico to the subtropical, humid region of Arkansas. However, more extensive testing of the GFFG methodology is required to evaluate its performance in different regimes and using different RFC's precipitation inputs. Expansion of the test area to several WFOs east of the ABRFC region is planned for fiscal year 2007.

As mentioned in Section 5, *Conclusions,* localization of ThreshR values has the potential to greatly improve GFFG at the grid or FFMP-basin scale. In flash-flood-susceptible areas, such as low-water crossings, estimates of bankfull flow may not represent a life-threatening flow. The development of a utility is planned to allow the Service Hydrologist at a WFO to input easily measured parameters, such as width of channel, depth of critical flow, location of site and a description of the site to estimate a critical flow using Manning's equation and produce a site-specific ThreshR value. The fact that the GFFG model is set up in a GIS environment allows for the relatively easy updating of this data in the original grid.

Another gridded ThreshR improvement would be accounting for the state of the channel at the time of issuance of GFFG. The current model assumes an empty channel and therefore will produce values that are likely too high in the midst of, or just after, a flood event. Some synthetic techniques are under evaluation at this time to estimate channel fullness at the grid-cell level.

In Section 2.1, *NWS HL-RMS*, the distributed modeling mode is described as "unconnected". It would be desirable to produce a GFFG value that accounts for routed, upstream flow. However, a widely-applicable calibration strategy for distributed routing parameters at the sub-basin level doesn't exist at this time. Future developments in distributed modeling or calibration strategies of those models will provide for a more robust, scalable GFFG model.

ABRFC's GFFG model has been accepted as an Advanced Hydrologic Prediction Services (AHPS) project for fiscal year 2007 to support the AHPS goal of delivering more specific and timely information on fast rising rivers. As such, funding will be available to accomplish much of this future work by the end of fiscal year 2007.

7. Acknowledgements

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Appendix A: Lookup Table Assigning Curve Numbers Based on NLCD Land Use-Land Cover and STATSGO Hydrologic Soil Group Data

| CLASS	DESCRIPTION	A	B	C	D
11	Open Water	100	100	100	100
12	Perennial Ice/Snow	100	100	100	100
21	Low Intensity Residential	57	72	81	86
22	High Intensity Residential	61	75	83	87
23	Commercial/Industrial/Transportation	89	92	94	95
30	Barren	77	86	91	94
31	Bare Rock/Sand/Clay	77	86	91	94
32	Quarries/Strip Mines/Gravel Pits	77	86	91	94
33	Transitional	43	65	76	82
41	Deciduous Forest	36	60	73	79
42	Evergreen Forest	36	60	73	79
43	Mixed Forest	36	60	73	79
50	Shrubland	35	56	70	77
51	Shrubland	35	56	70	77
60	Non-Natural Woody	35	58	71	78
61	Orchards/Vineyards/Other	35	58	71	78
71	Grasslands/Herbaceous	49	69	79	84
81	Pasture/Hay	49	69	79	84
82	Row Crops	67	78	85	89
83	Small Grains	63	75	83	87
84	Fallow	76	85	90	93
85	Urban/Recreational Grasses	39	61	74	80
91	Woody Wetlands	36	60	73	79
92	Emergent Herbaceous Wetlands	49	69	79	84
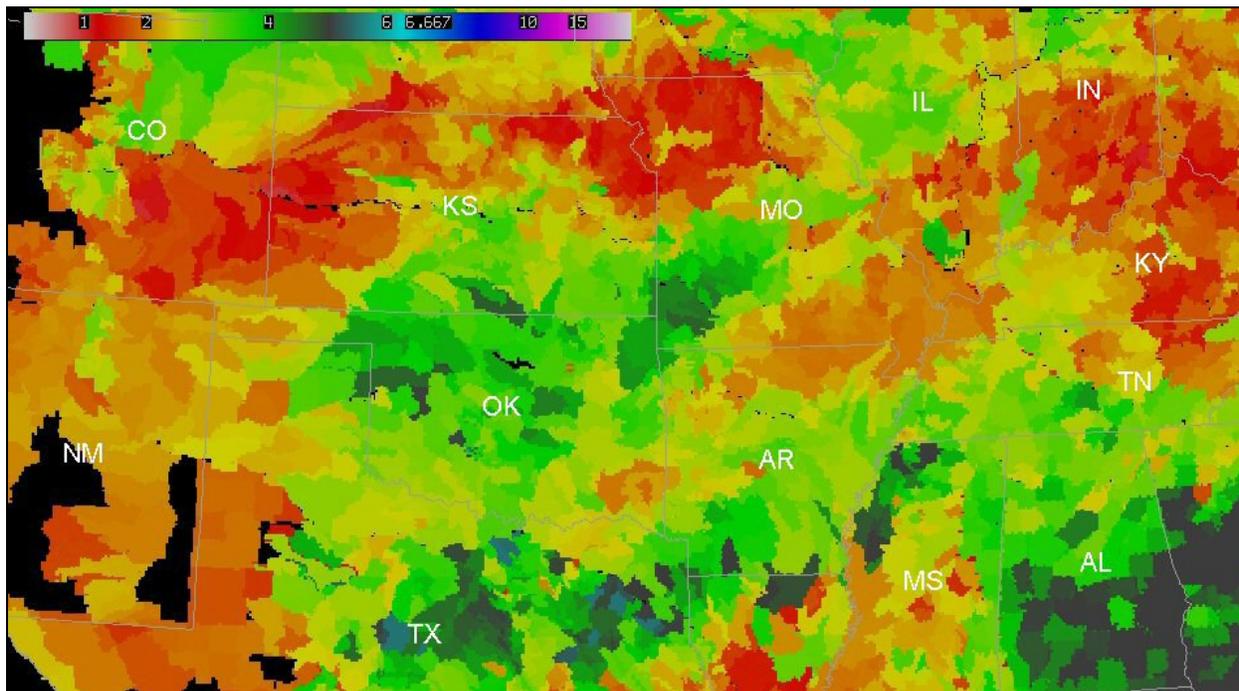
Figure 10: Southern Plains and Lower Mississippi River Valley Region, Lumped-Basin, 3-hour Flash Flood Guidance Values from all or parts of 6 different RFCs, Oct. 27, 2006, 12Z. Units are in.
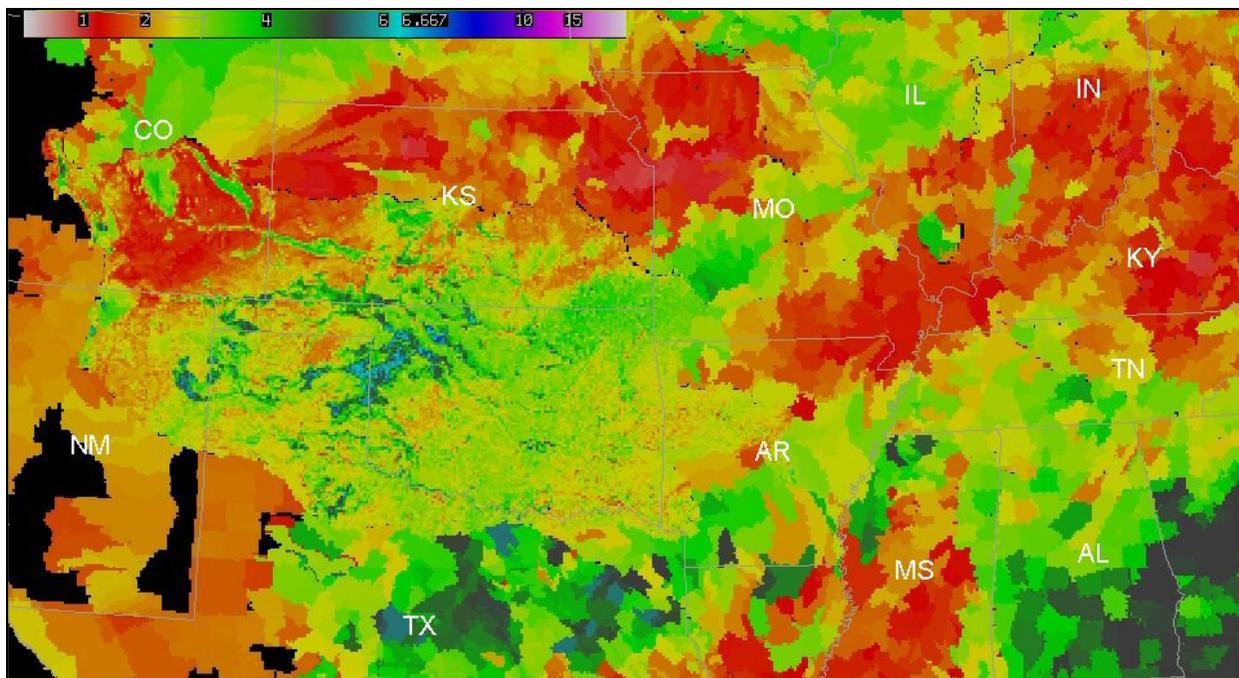

Figure 11: Southern Plains and Lower Mississippi River Valley Region, Lumped-Basin *(Gridded in ABRFC's area)*, 3-hour Flash Flood Guidance Values from all or parts of 6 different RFCs, Oct. 27, 2006, 18Z. Units are in.

Appendix C: Impact of Precipitation Distribution on Lumped-Basin and Gridded Flash Flood Guidance.
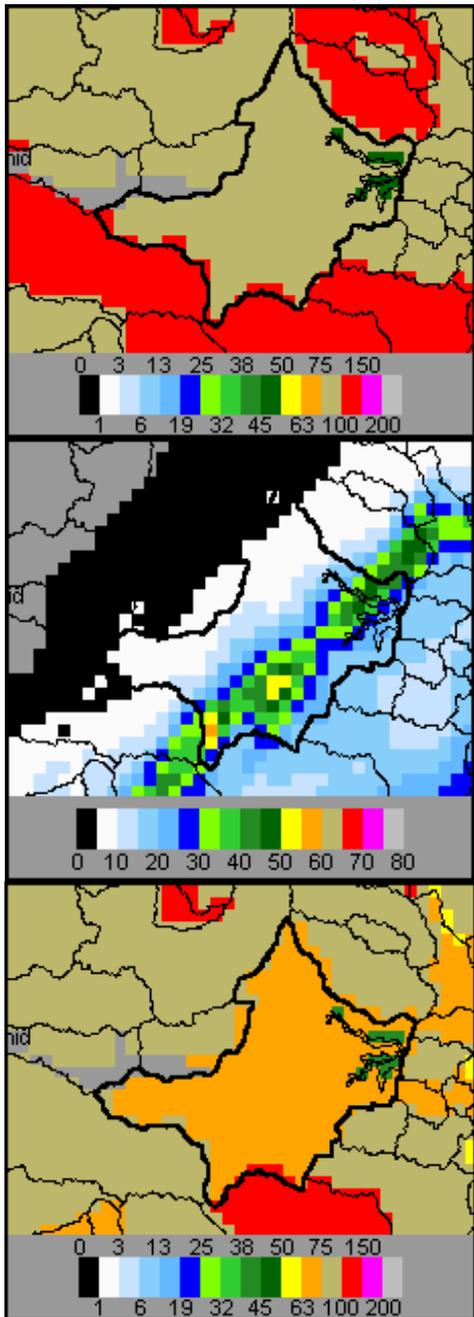
Figure 12:   3-hour Lumped-Basin FFG changes as a result of precipitation field in middle pane, September 17, 2006. Units are mm.
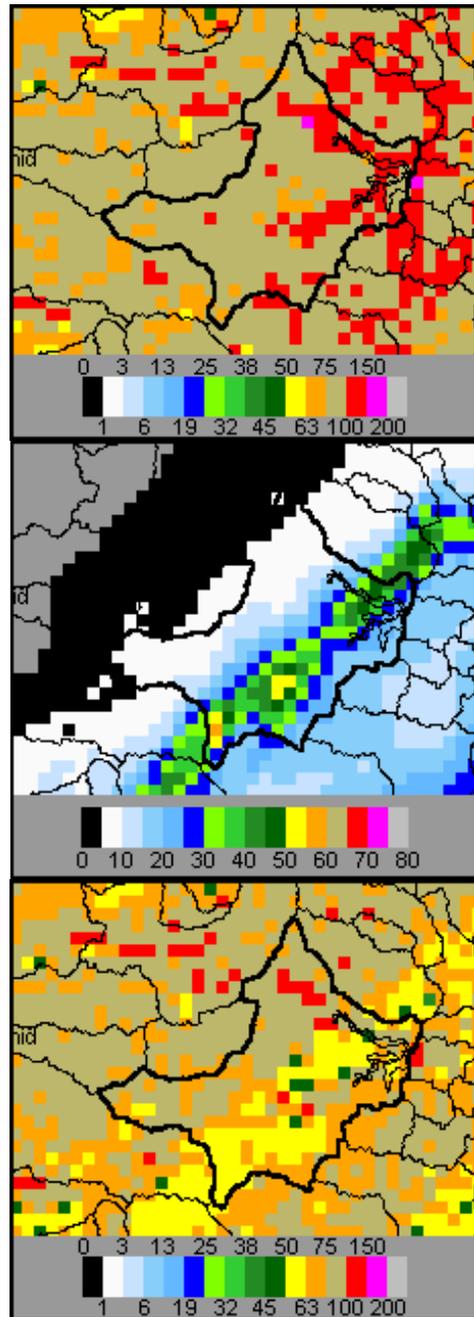
Figure 13: 3-hour Gridded FFG changes as a result of precipitation field in middle pane, September 17, 2006, 18Z. Units are mm