Use of the Flash Flood Monitoring and Prediction (FFMP) Program on the 23-24 August 2003 Flash Flood Event in Southern Utah

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Introduction

Flash flood monitoring and prediction is considered integral to severe weather operations across the intermountain western United States. Between 1 January 2000 and 29 February 2004 - which covers three convective seasons - there were 67 flash flood events reported in Utah alone (Table 1). Most significantly, flash flooding accounted for nearly 7 million dollars in property damage in Utah over this period, by far its most damaging severe weather phenomenon. Utah's complex terrain, which includes numerous dry washes and slot canyons capable of producing flash flooding with relatively small rainfall amounts, combined with the fact that more than 1.3 million Utah residents participate in outdoor recreation activities annually, translating to 82%, or nearly 4/5ths of the State's population aged 16 and older (Outdoor Industry Foundation 2004), compounds the flash flood threat to create very dangerous severe weather situations. Additionally, the number of visitors to the National Parks, Monuments, Recreation Areas, and State Parks in Utah totaled 14.5 million in 2003 (Utah Division of Travel Development 2004).

The case presented here describes a severe flash flood event that took place on 23-34 August 2003 in southern Utah. Numerous flash floods were observed and reported during the afternoon of the 23rd, extending into the evening hours of the 24th. In all, the Salt Lake City NWS Weather Forecast Office (SLC WFO) issued nine flash flood warnings during this event, all of which verified, and with a false alarm rate of 0.11 and an average lead time of 48 minutes. Table 2 shows individual warning times, locations, and verification (with lead time). Emphasis in this paper is placed on describing the application of the Flash Flood Monitoring and Prediction program (FFMP; Smith et al 2000) to warning operations for this event. Lastly, application of the recently developed Flash Flood Potential Index (FFPI; Smith 2003), which provides detailed physiographic information for individual FFMP basins and thus helping the warning forecaster better identify basins more susceptible to flash flooding, will be described.

Synoptic Overview

The general synoptic pattern in place over the western U.S. at midday on 23 August was characterized by a long wave trough centered over coastal British Columbia, Canada, with a short wave just moving onshore into central California. Ahead of this trough, abundant moisture was pumped northward through the desert southwest and eastern Great Basin, as is clearly evident in the GOES WV imagery at 1800 UTC 23 August (Fig. 1). This moisture plume is also depicted in the GOES-derived precipitable water (PW) product (Fig. 2), computing PW amounts of over 1 in along the plume's axis, then decreasing to about a half an inch extending northwest from this axis into extreme northwest Utah. This was significantly above average (Fig. 3). As is typical in the western U.S., this moisture plume was a significant factor in the development of severe convection and flash flooding over southern Utah. Finally, a weak short wave was evident over southern Nevada in the GFS 400 mb analysis at 1800 UTC (see Fig. 1), and forecast to eject northeast into southwestern Utah over the course of the afternoon. The moist conditions, combined with this weak upper level triggering mechanism and daytime heating off the higher terrain in southern Utah, were likely the primary ingredients responsible for convective development that afternoon. Though ideally most flash flooding conditions in Utah are a result of above average PW and weak mid-level winds - producing very slow-moving cells and heavy rain - the vertical shear profile was conducive to cell backbuilding and training.

Overview of Convective Development between 1900 and 2030 UTC 23 August

By early afternoon, relatively weak convection was decreasing over extreme southern Utah, and subsequently developed further north over higher terrain. A GOES visible satellite loop covering the period between 1900 and 2100 UTC (Fig. 4 NOTE: Black box on last frame denotes primary area of interest) shows this development. A closer examination of this activity is shown in figure 5, displaying the composite reflectivity detected by the Cedar City, Utah (KICX) WSR-88D at 1900 UTC. Convection continued to increase in coverage and intensity through 2030 UTC, again as depicted by the KICX composite reflectivity image from this time (Fig. 6). The remainder of this paper will focus on the thunderstorm over and just to the west of Capitol Reef National Park (denoted in figure 6), which is just to the west of Caineville, UT. This very strong thunderstorm moved east and along the drainages feeding the Fremont River over the following hour.

Use of the WSR-88D to Diagnose Flash Flood Occurrence and Potential

Figure 7 is a loop of 0.5 o base reflectivity from KICX between 2005 and 2045 UTC. Note the eastward movement of the thunderstorm

approaching Capitol Reef NP - also appearing to be to the right of the area mean storm motion. Further making this a dangerous situation is the
fact that this cell was moving downstream and along the drainages feeding the Fremont River, which runs nearly parallel to Utah State Highway
24. The WSR-88D Precipitation Processing System (PPS) calculated peak storm total precipitation (STP) amounts from this cell of 1.5 to 2.0
inches as it moved steadily east (Fig. 8). A methodology often employed in flash flood warning situations in complex terrain is to combine and
fade WSR-88D STP imagery with the high-resolution digital terrain image on AWIPS, allowing the warning forecaster to consider terrain when
determining the potential for flash flooding. Using this display method on this particular cell confirms its movement and position along and near
the drainages feeding the Fremont River (Fig. 9). This further heightened the flash flood situational awareness.

The Flash Flood Monitoring and Prediction (FFMP) Program and Its Use on 23 August

The core function of FFMP is to map reflectivity information from radar bins to pre-defined hydrologic basins. The program uses the Digital Hybrid Reflectivity (DHR) product to derive rainfall rates and associated rainfall accumulations from each volume scan, on each basin under the
radar umbrella (Fig. 10), and over user-specified time periods (as little as 30 min and as much as 6 hr). These data are also compared to RFC-generated Flash Flood Guidance (FFG). Users may view this information in table form or graphically in D2D whereby ranges of rainfall accumulation, rate, and FFG-exceeding values are color-coded. A particularly powerful display capability in FFMP provides this same information in line-graph form for each basin by displaying each parameter from the last volume scan backwards (to the right on the graph) to 8
hours. The primary benefit of FFMP is to provide basin-specific rainfall accumulation rather than just by radar bin as is available with standard
WSR-88D precipitation products. This allows for a truer hydrologic perspective on the effects of heavy rainfall. Despite this, FFMP does have its
limitations. Namely, extensive work is required to initially set up and customize the basins, possibly incorrect DHR-basin mapping , the user must understand streamflow from basin to basin, radar limitations still exist, FFG development is inconsistent from RFC to RFC, and the general
crudeness of determining FFG (e.g., doesn't consider physiographic character of basin, nor ground saturation, and specificity is limited to WFO
zones). The use of FFMP at the SLC WFO, which was preceded by the use of the Areal Mean Basin Estimated Rainfall program (Amber; Jendrowski and Davis 1998), has greatly improved flash flood warning performance (Fig. 11). Note the increasing POD and CSI, and decreasing FAR, since use of Amber began in 2000, then with the transition to full FFMP use in operations beginning with the 2003 convective
season.

Figure 12 presents the FFMP display first shown after starting the program under the AWIPS SCAN menu - in this case for KICX. Shown is a
display of counties within the KICX WSR-88D umbrella, each colored, in this case, based on the maximum basin rainfall accumulation within a
county over the last hour ending at 2045 UTC. The FFMP Threat Table in the left of figure 12 provides basin details for each county. These include from left to right: maximum basin rainfall accumulation within the county over a user-selectable time period from 30 min to 6 hr, maximum
rainfall rate, basin FFG, the ratio of maximum basin accumulation to FFG, and finally the difference between maximum basin accumulation and
FFG. The user may display basin accumulation or rate in the D2D graphics window, in addition to ranking the counties in the Threat Table by
maximum basin rainfall accumulation or rate. For the case of 23 August at 2045 UTC, two counties in south central Utah exhibited 1-hr basin
rainfall accumulations of over 1.5 inches.

By clicking on a particular county in the FFMP table, the user is able to view rainfall information for each basin within that county. This next level
of detail is shown in figure 13, depicting basin details ranked by maximum basin rainfall accumulation. The D2D graphics window displays this
basin rainfall accumulation in plan view. The heavy rainfall that occurred within drainages feeding the Fremont River on the 23rd is depicted in
this graphic (the "X" is centered on the basin with the largest rainfall accumulation). By ranking basins by maximum rainfall rate - and subsequently repositioning the "X" in the D2D window on the basin with the highest rainfall rate - it's possible to determine which basins are within the most serious near-term threat. Note that by ranking basins by rate at 2045 UTC, the basin with the highest rate was actually farther
down-drainage than the basin with the highest rainfall accumulation (Fig. 14 NOTE: The D2D display in this figure still shows maximum rainfall
accumulation for demonstration purposes).

To examine basin information in further detail, the user can right-click on the basin id in the Threat Table basin column to display the basin's Flash Flood Analysis graph. This graph shows basin rainfall accumulation, rate, and FFG in a time-series mode, with time (past) to the right. In
an idealized sense, flash flooding is possible wherever accumulation is greater than FFG on the graph. Figure 15 shows the Flash Flood Analyses graph for a basin just west of Capitol Reef NP at 2045 UTC 23 August. This basin received nearly 1.5 inches of rainfall up to this time,

while also experiencing a rainfall rate of just over 4 inches per hour just prior.

A flash flood warning was issued at 241 PM MDT (2041 UTC) for Western Wayne County in Utah, including for areas along the Fremont River in and near Capitol Reef NP, effective until 445 PM MDT. Not long after the warning was issued, park officials rescued a woman trapped while attempting to cross the Fremont River inside the park. This dramatic rescue was captured on video by a local Salt Lake City television news crew. Utah State Highway 24 was closed from Caineville to Capitol Reef NP due to near bankfull conditions along the Fremont River which is fed from the Sulphur and Deep Creek drainages. Later that evening at approximately 0000 UTC , a river gauge along the Fremont River in Caineville recorded a 7 ft rise and a volume flow increase of nearly 10000 cfs (Fig. 16).

The Flash Flood Potential Index (FFPI)

One limitation of FFMP is its inability to discern basin physiographic character. To FFMP, basin rainfall accumulations, rate, and FFG-exceeding values are treated equally regardless of a basin's physiographic make up, such as soil type, slope, or forest cover. Greg Smith of the NWS Colorado Basin River Forecast Center has developed a theoretical index that represents a level of hydrologic response to heavy rainfall for each basin. The Flash Flood Potential Index considers five basin physiographic characters in its derivation: soil type, forest cover, land use, slope, and vegetation type. Subjective factors of importance have been applied to each of these parameters to derive an index of 1 to 10. This index, originally computed on a 4-km grid, has been interpolated to each FFMP basin and viewable using ArcView software (Fig. 17). This allows the user to interactively roam, zoom, and toggle on and off various graphics - such as spotter locations, rivers, highways and roads - along with FFPI information. Currently, forecasters view the FFPI on a platform separate from AWIPS since ArcView is not available for the Linux operating system. This, however, only slightly reduces its value to a flash flood warning situation. This index is especially useful when monitoring potential flash flooding in areas of complex terrain. Southern Utah basin characteristics range from, for example, gradually-sloped or flat, forested or non-forested terrain, to steep slick rock canyons. These steeply sloped and sparsely vegetated areas are especially capable of inducing dangerous flash flooding with precipitation amounts that would be considered relatively light in areas east of the Rocky Mountains. The FFPI enables the warning forecaster to further differentiate the flash flood thread created by convective cells producing similar rainfall amounts over equally sized basins.

The physiographic character of basins in and around Capitol Reef NP is vividly depicted by the FFPI for this area (Fig. 18). The area, which is characterized by dry washes and narrow, steep slick rock canyons, is particularity susceptible to flash flooding - just as occurred on this day. This high FFPI near the cell of interest provided the warning forecaster on this day with valuable information to use in the flash flood warning decision making process.

A major limitation of FFPI is the requirement to view its information outside of FFMP. Future work will explore resolving this issue, possibly developing an objective method to directly incorporate this information in to the FFG used in FFMP.

Use of FFMP on the Weather Event Simulator (WES)

The capability to run and display FFMP on the SLC WFO Weather Event Simulator (WES) was introduced with WES software version 2.0, made available just prior to the spring 2004 training period. Because monitoring and predicting flash flood events is - as stated earlier - so important to SLC WFO operations, forecasters directed to complete two required WES drills were assigned this particular case for one of the drills. The drill emphasized the general operation and manipulation of the FFMP interface, and further asked forecasters what, if any, statements or warnings should be issued for two particular storms from this case: a null case, and the storm near Capitol Reef NP. Future use of the FFMP in warning decision making training will move beyond the general operation of FFMP and expand to include full incorporation of environmental situational awareness and the additional decisional aspects inherent to a true convective warning environment.

References

Jendrowski, Paul, and R. S. Davis, 1998: Use of geographical information systems with the areal mean basin estimated rainfall algorithm. Preprints, Special Symposium on Hydrology, Phoenix, AZ, Amer. Met. Soc., 129-133

Outdoor Industry Foundation. 2004: Outdoor Recreation and Participation Study: A State by State Perspective, 32 pages.

Smith, Greg, 2003: Determining the hydrologic response of FFMP basins to heavy rain by analyzing their physiographic characteristics. A white paper available at the NWS Colorado Basin River Forecast Center web site at http://www.cbrfc.noaa.gov/papers/ffp_wpap.pdf

Smith, Steve. B., M. T. Filiaggi, M. Churma, J. Roe, M. Glaudemans, R. Erb, L. Xin. 2000: Flash Flood Monitoring and Prediction In AWIPS 5 and beyond. Preprints, 15th Conf. on Hydrology, AMS, Long Beach, CA, 229-232.

Utah Division of Travel Development. 2004: 2004 Situational Analysis, 3 pages.

Figure 1

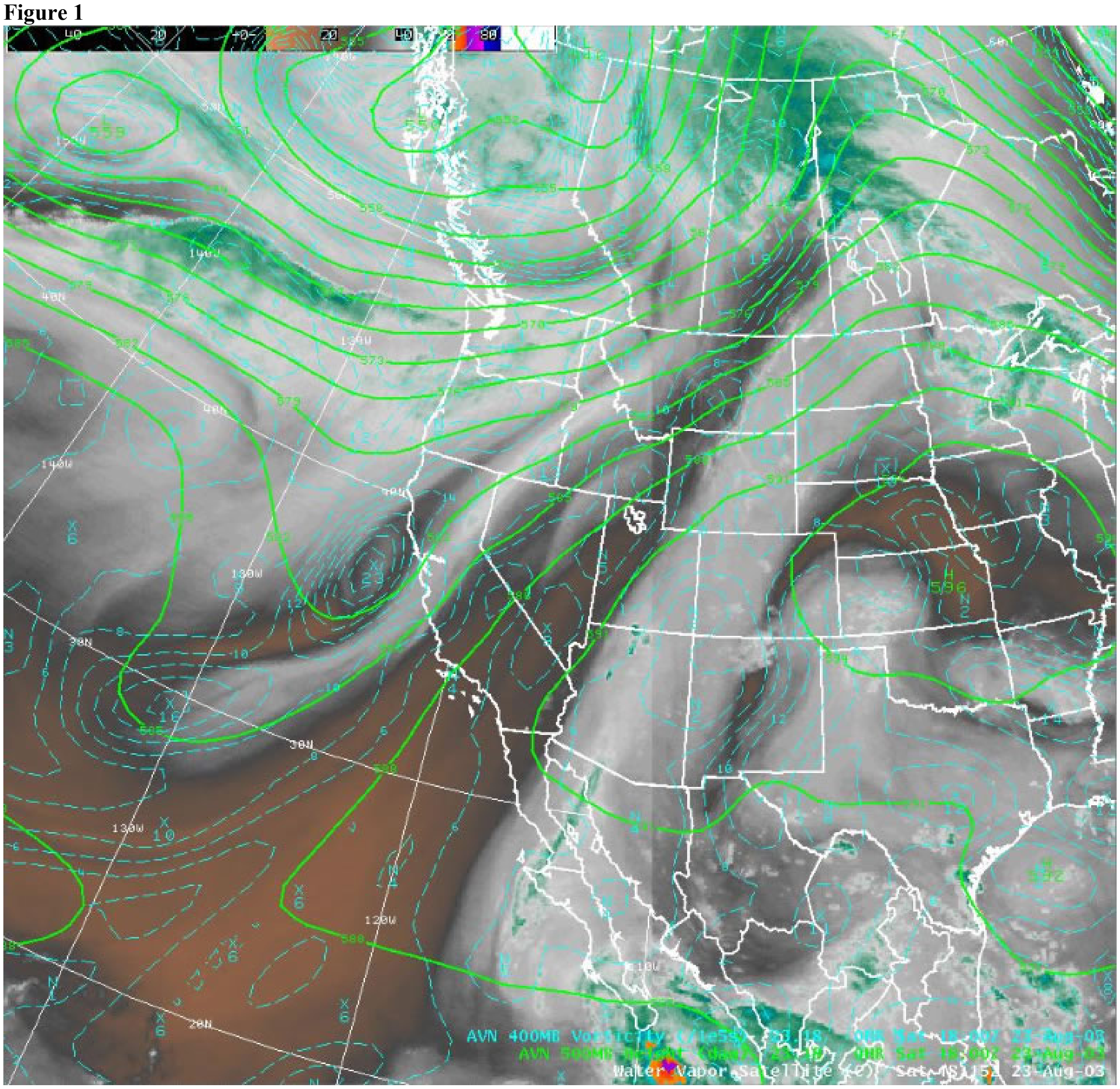


Figure 2

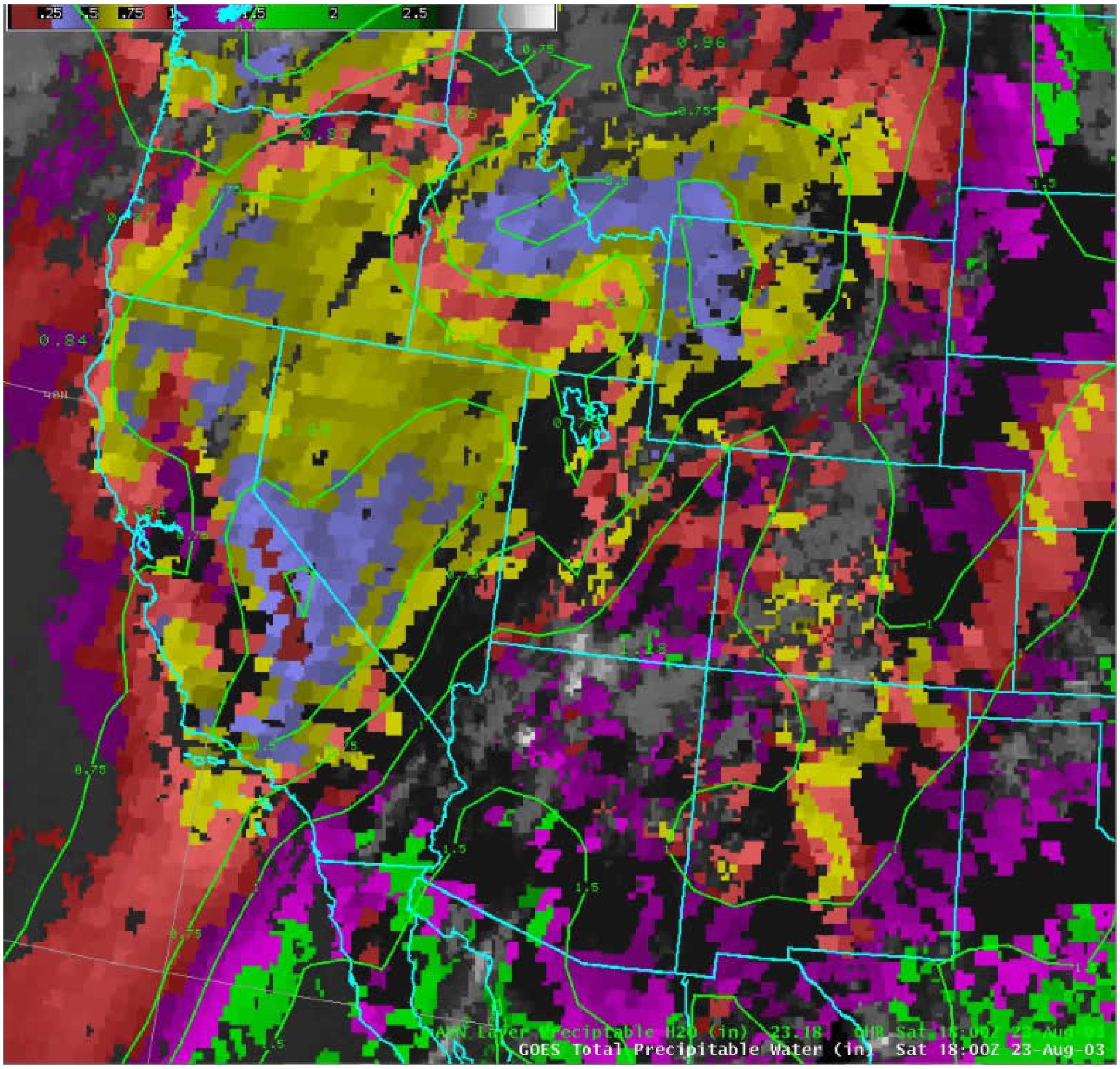

.25 .5 .75 1 1.5 2 2.5
GOES Total Precipitable Water (in) Sat 18:00Z 23-Aug-03

Figure 3

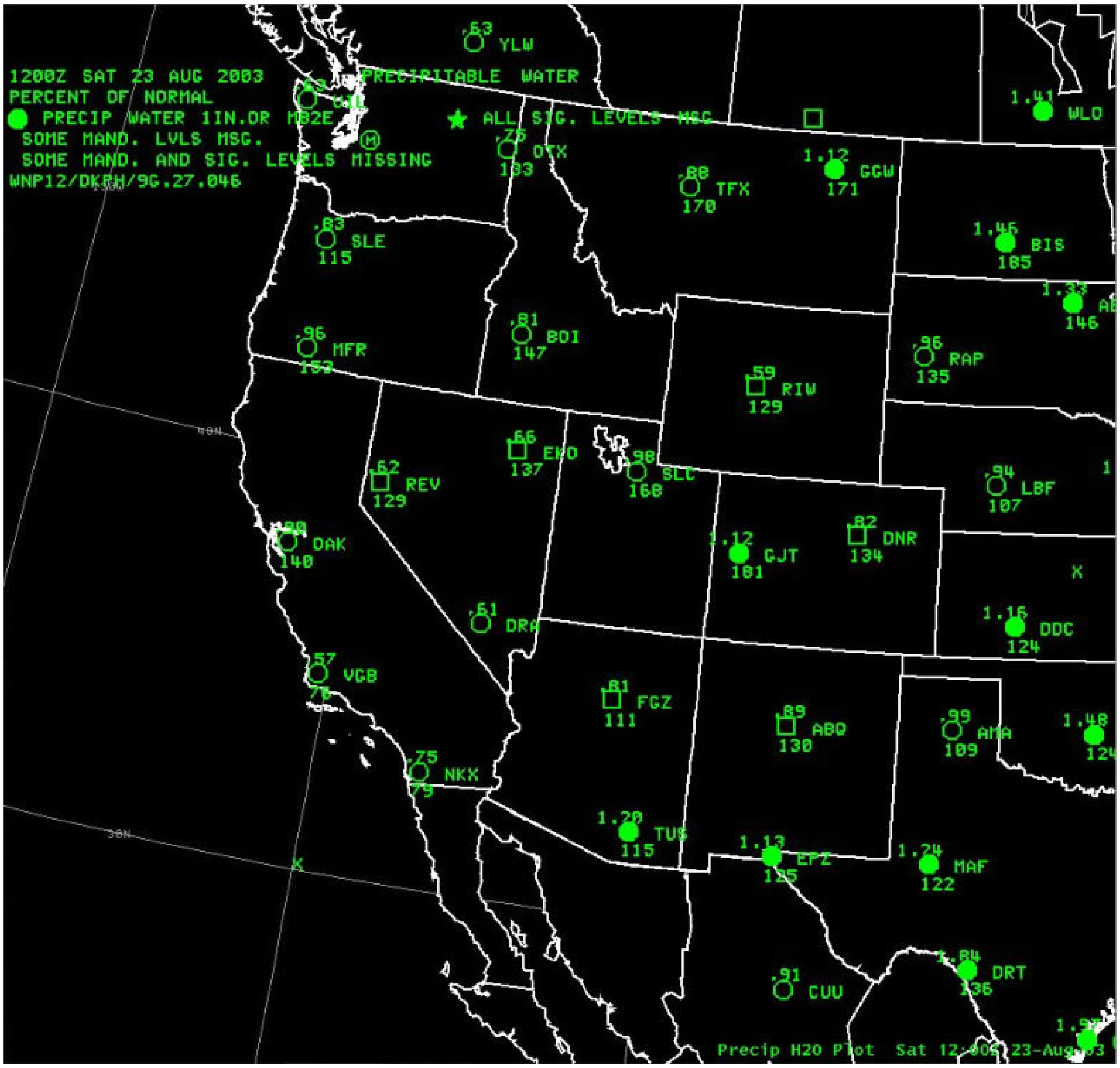

1200Z SAT 23 AUG 2003
PERCENT OF NORMAL
PRECIPITABLE WATER
PRECIP WATER 1IN.OR
ALL SIG. LEVELS MSG
SOME MAND. LVLS MSG.
SOME MAND. AND SIG. LEVELS MISSING
WNP12/DKPH/9G.27.046
.63 YLW
1.41 WLO
.76 OTX 133
.88 TFX 170
1.12 GGW 171
.83 SLE 115
1.46 BIS 185
.81 BOI 147
.96 MFR
.59 RIW 129
.96 RAP 135
.66 EKO 137
.98 SLC 168
.62 REV 129
.94 LBF 107
1.12 GJT 181
.82 DNR 134
OAK 140
.61 DRA
1.16 DDC 124
.57 VGB
.81 FGZ 111
.89 ABQ 130
.99 AMA 109
.75 NKX 79
1.20 TUS 115
1.13 EPZ 125
1.24 MAF 122
DRT
.91 CUU
Precip H2O Plot Sat

Figure 4

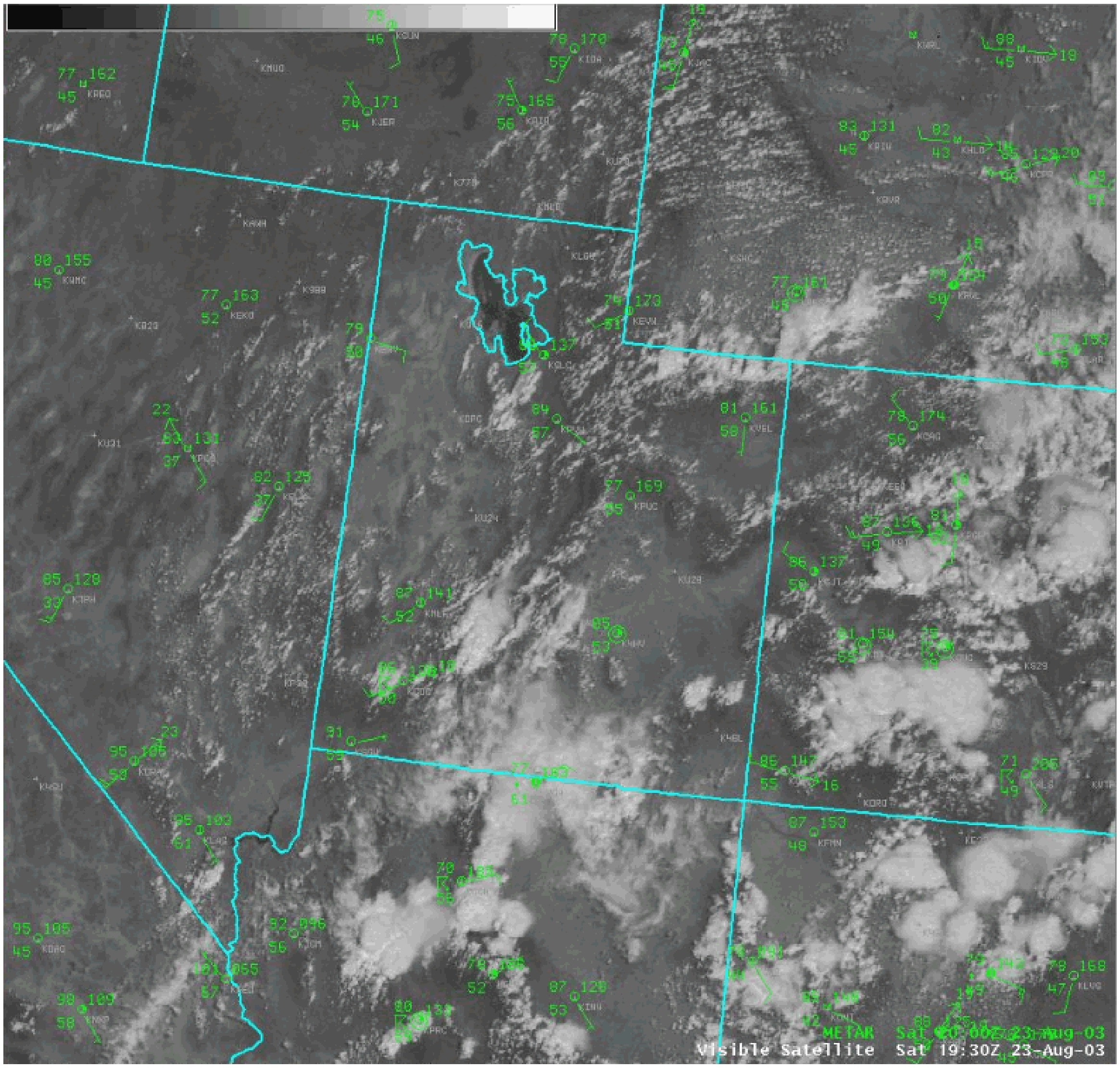

METAR Sat 20:00Z 23-Aug-03
Visible Satellite Sat 19:30Z 23-Aug-03

Figure 5

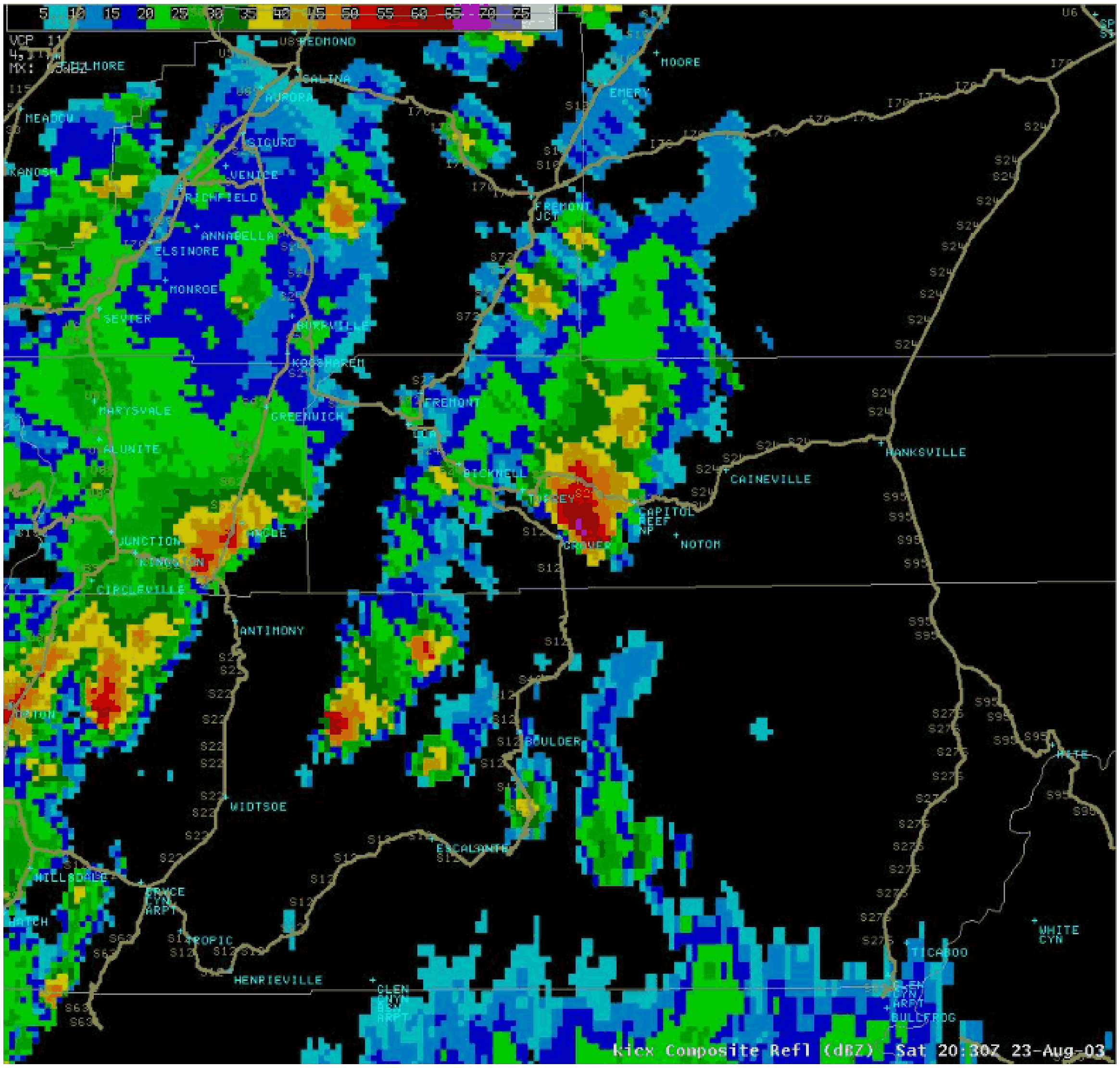


Figure 6

Figure 7

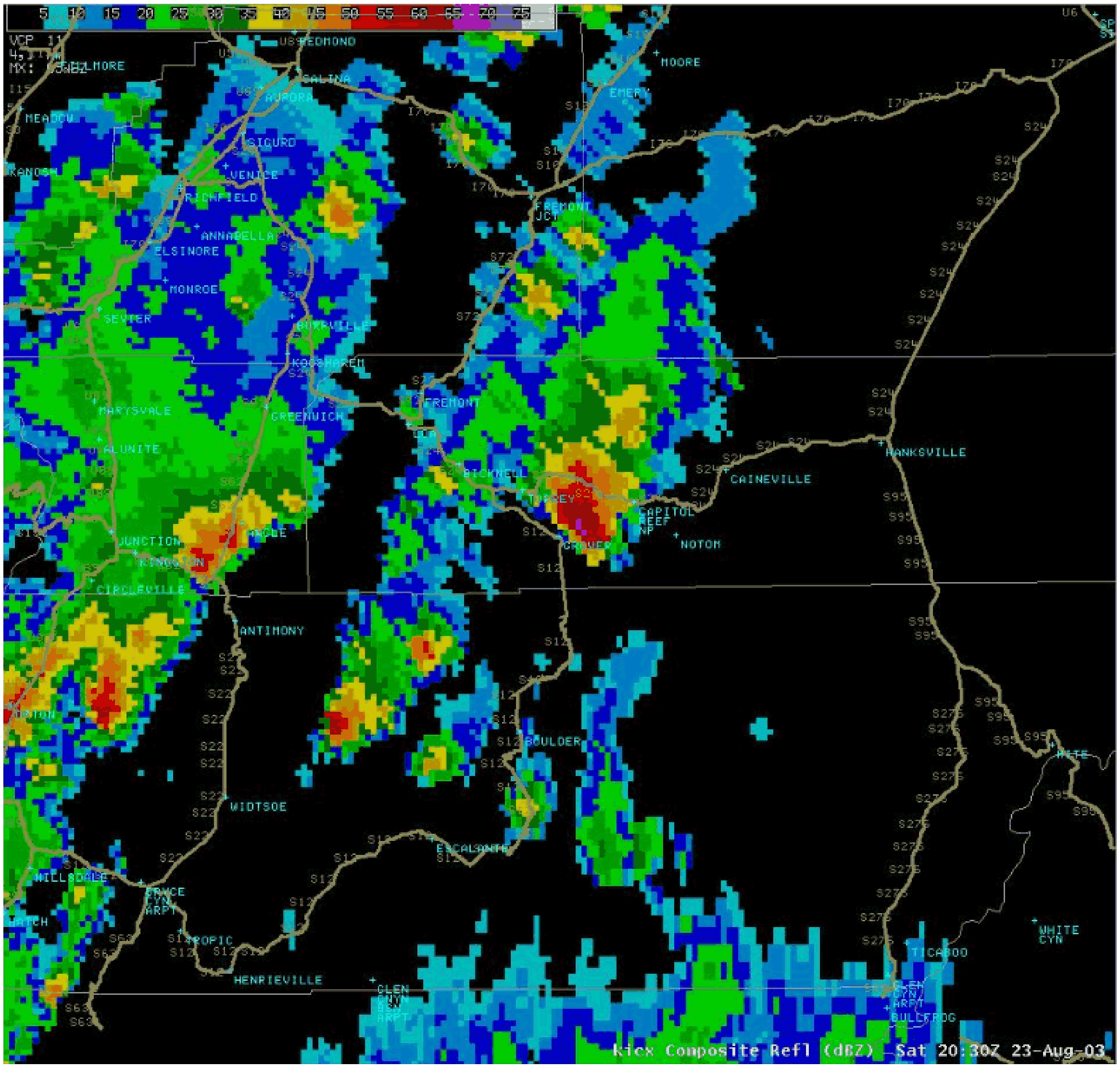

5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
VCP 11
REDMOND
SALINA
MOORE
AURORA
EMERY
MEADOW
SIGURD
VENICE
RICHFIELD
FREMONT JCT
ANNABELLA
ELSINORE
MONROE
SEVIER
KOOSHAREM
MARYSVALE
GREENWICH
FREMONT
ALUNITE
HANKSVILLE
BICKNELL
CAINEVILLE
TORREY
CAPITOL REEF NP
NOTOM
GROVER
JUNCTION
KINGSTON
CIRCLEVILLE
ANTIMONY
BOULDER
WIDTSOE
ESCALANTE
HILLSDALE
BRYCE CYN ARPT
TROPIC
HENRIEVILLE
WHITE CYN
TICABOO
BULLFROG
Kicx Composite Refl (dBZ) Sat 20:30Z 23-Aug-03

Figure 8

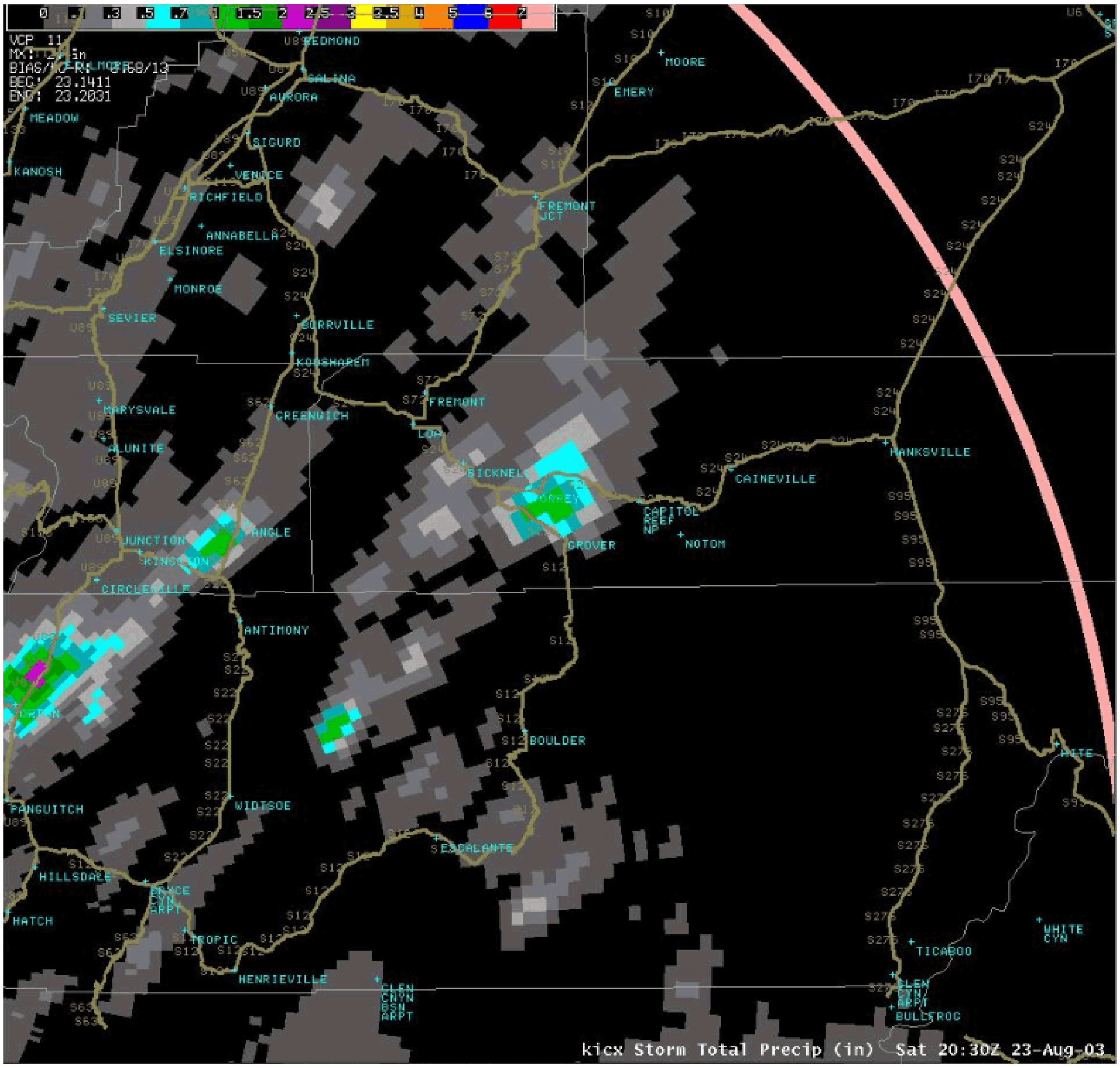

kicx Storm Total Precip (in) Sat 20:30Z 23-Aug-03
HANKSVILLE
CAINEVILLE
BICKNELL
FREMONT
GROVER
BOULDER
ESCALANTE
PANGUITCH
RICHFIELD
SALINA
TICABOO

Figure 9

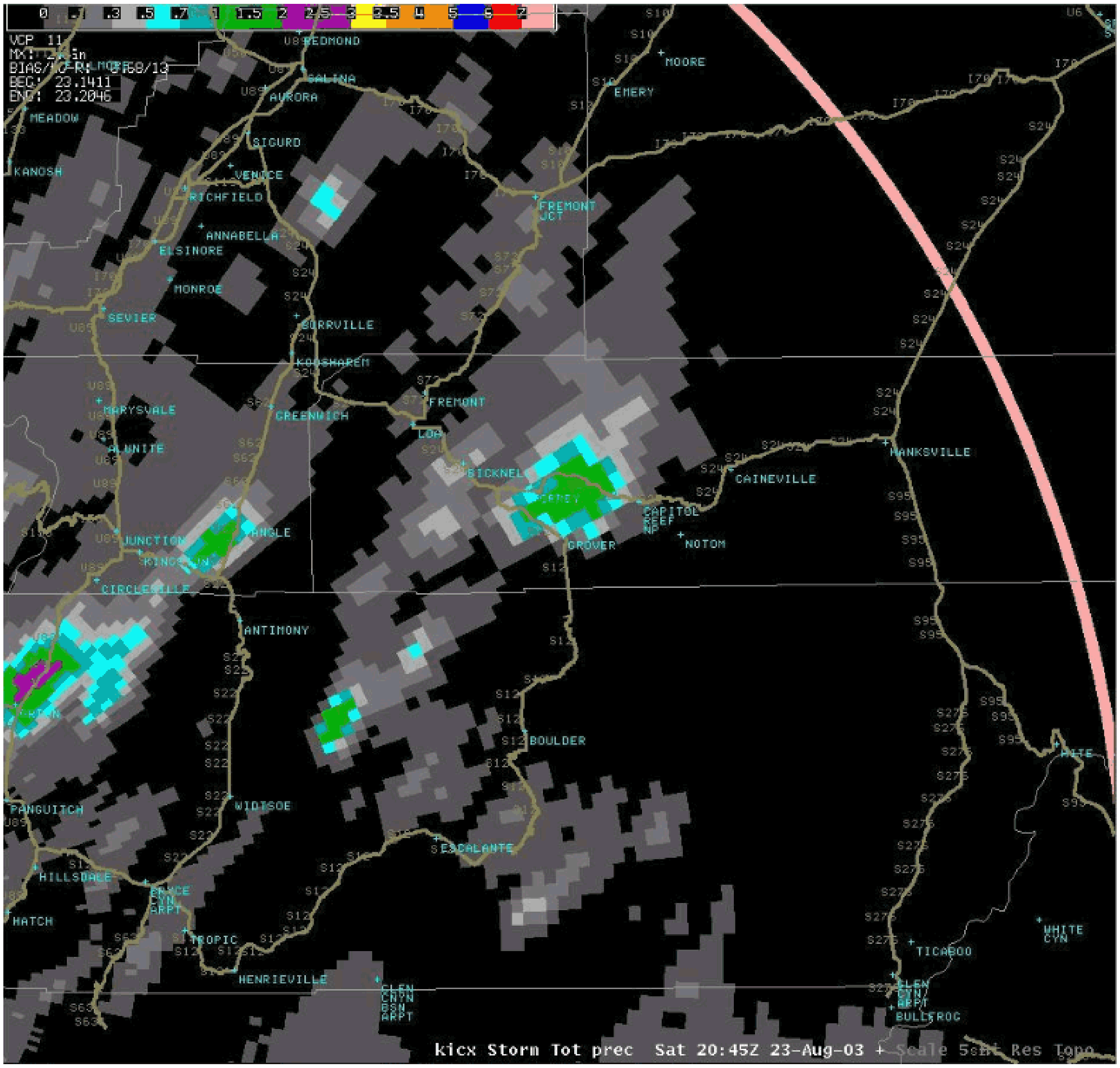

kicx Storm Tot prec Sat 20:45Z 23-Aug-03
REDMOND
SALINA
AURORA
SIGURD
VENICE
RICHFIELD
ANNABELLA
ELSINORE
MONROE
SEVIER
KANOSH
MEADOW
MOORE
EMERY
FREMONT JCT
BURRVILLE
KOOSHAREM
FREMONT
GREENWICH
LOA
BICKNELL
MARYSVALE
ALUNITE
JUNCTION
KINGSTON
ANGLE
CIRCLEVILLE
ANTIMONY
CAINEVILLE
HANKSVILLE
CAPITOL REEF NP
GROVER
NOTOM
BOULDER
ESCALANTE
WIDTSOE
PANGUITCH
HILLSDALE
HATCH
BRYCE CYN ARPT
TROPIC
HENRIEVILLE
GLEN CNYN BSN ARPT
TICABOO
WHITE CYN
BULLFROG
HITE

Figure 10

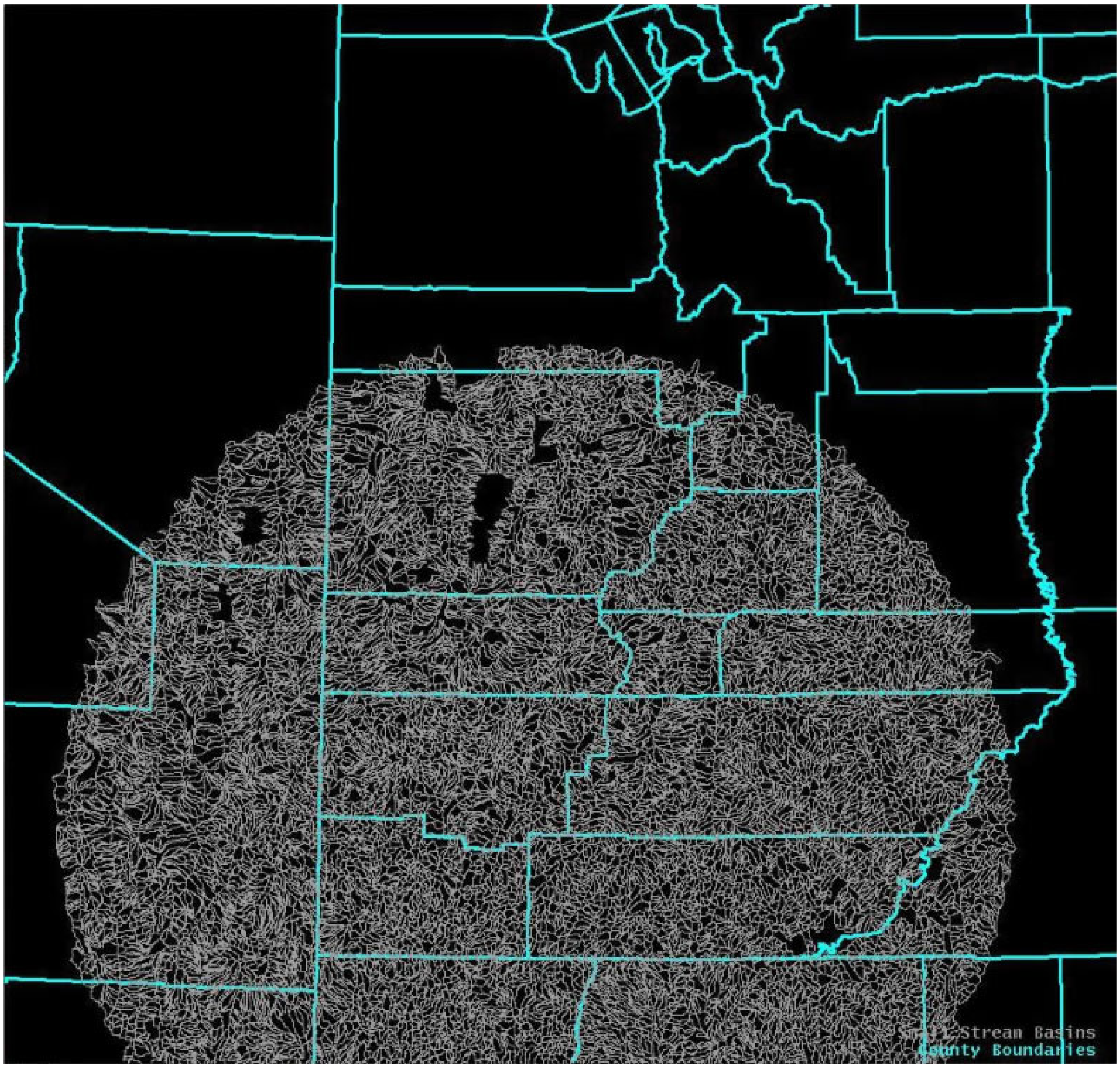


Figure 11

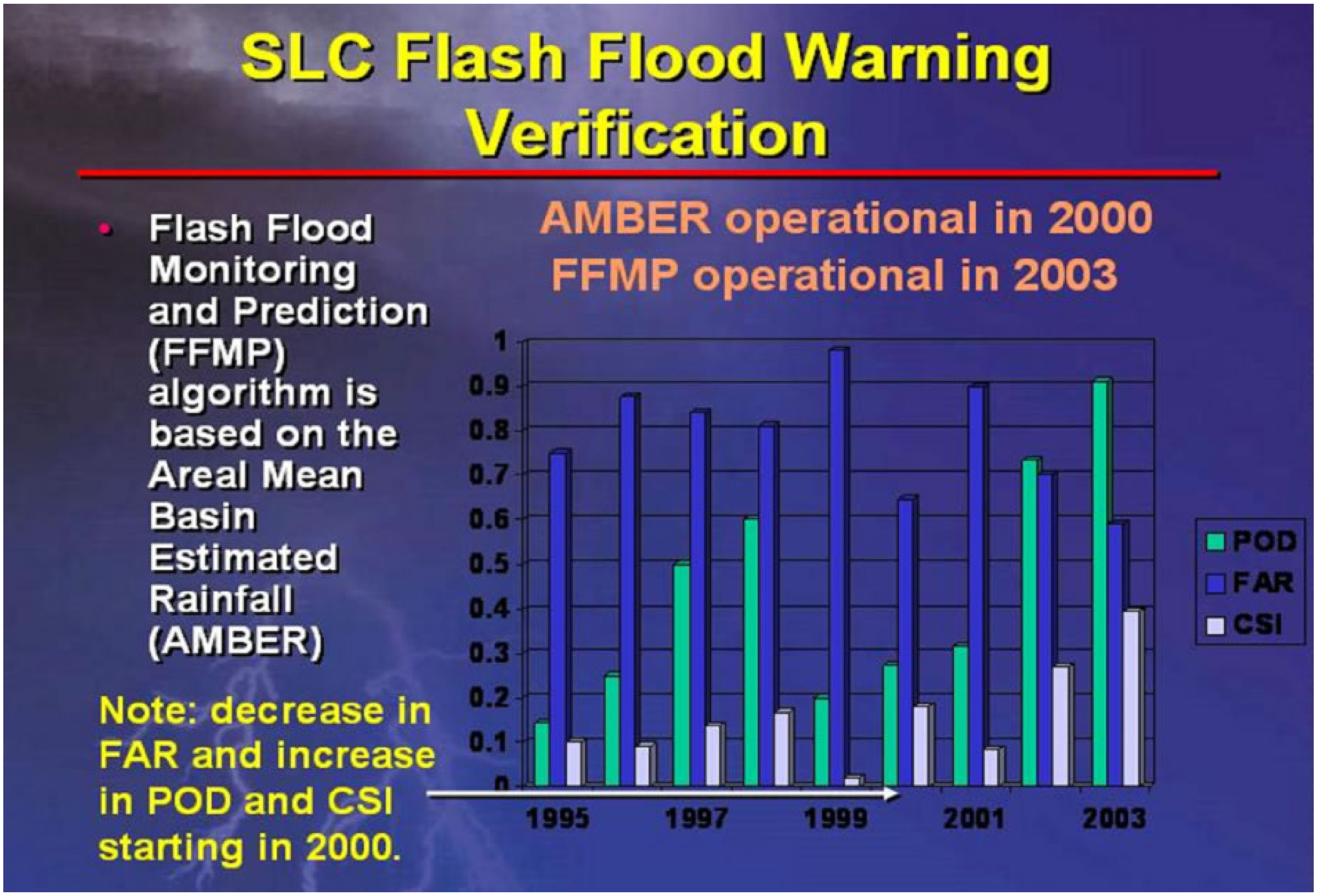

SLC Flash Flood Warning Verification
Flash Flood Monitoring and Prediction (FFMP) algorithm is based on the Areal Mean Basin Estimated Rainfall (AMBER)
AMBER operational in 2000
FFMP operational in 2003
Note: decrease in FAR and increase in POD and CSI starting in 2000.
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1995
1997
1999
2001
2003
POD
FAR
CSI

Figure 12

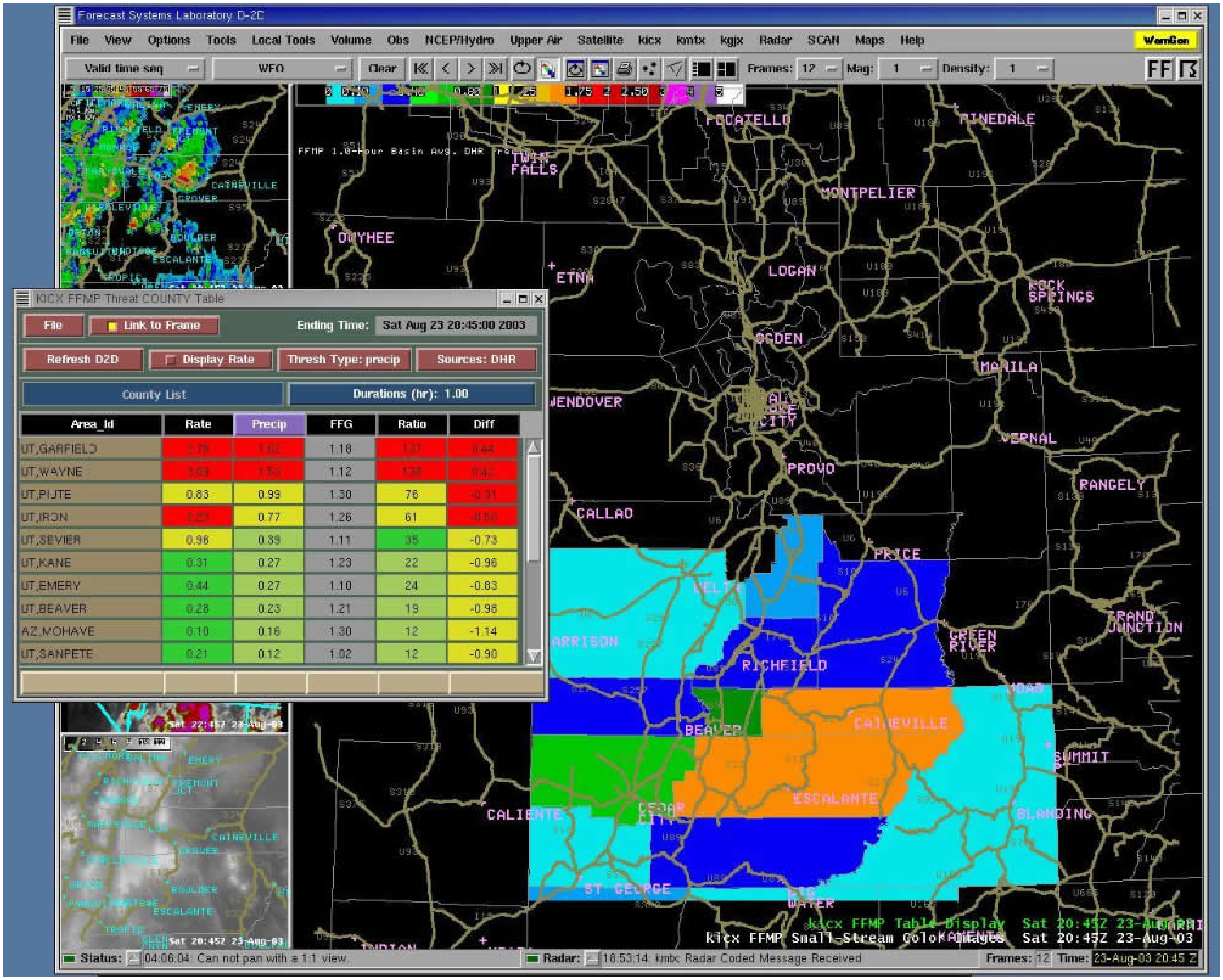

Forecast Systems Laboratory D-2D
File View Options Tools Local Tools Volume Obs NCEP/Hydro Upper Air Satellite kicx kmtx kgjx Radar SCAN Maps Help
WarnGen
Valid time seq
WFO
Clear
Frames: 12
Mag: 1
Density: 1
FFMP 1.0-Hour Basin Avg. DHR
KICX FFMP Threat COUNTY Table
File
Link to Frame
Ending Time: Sat Aug 23 20:45:00 2003
Refresh D2D
Display Rate
Thresh Type: precip
Sources: DHR
County List
Durations (hr): 1.00
Area_Id Rate Precip FFG Ratio Diff
UT,GARFIELD 1.18
UT,WAYNE 1.12
UT,PIUTE 0.83 0.99 1.30 76
UT,IRON 0.77 1.26 61
UT,SEVIER 0.96 0.39 1.11 35 -0.73
UT,KANE 0.31 0.27 1.23 22 -0.96
UT,EMERY 0.44 0.27 1.10 24 -0.83
UT,BEAVER 0.28 0.23 1.21 19 -0.98
AZ,MOHAVE 0.10 0.16 1.30 12 -1.14
UT,SANPETE 0.21 0.12 1.02 12 -0.90
POCATELLO
PINEDALE
TWIN FALLS
MONTPELIER
OWYHEE
ETNA
LOGAN
ROCK SPRINGS
OGDEN
MANILA
WENDOVER
SALT LAKE CITY
VERNAL
PROVO
RANGELY
CALLAO
PRICE
GRAND JUNCTION
GREEN RIVER
RICHFIELD
BEAVER
CAINEVILLE
SUMMIT
ESCALANTE
CALIENTE
CEDAR CITY
BLANDING
ST GEORGE
kicx FFMP Table Display Sat 20:45Z 23-Aug-03
kicx FFMP Small-Stream Color Images Sat 20:45Z 23-Aug-03
Status: 04:06:04 Can not pan with a 1:1 view.
Radar: 18:53:14 kmtx Radar Coded Message Received
Frames: 12
Time: 23-Aug-03 20:45 Z

Figure 13

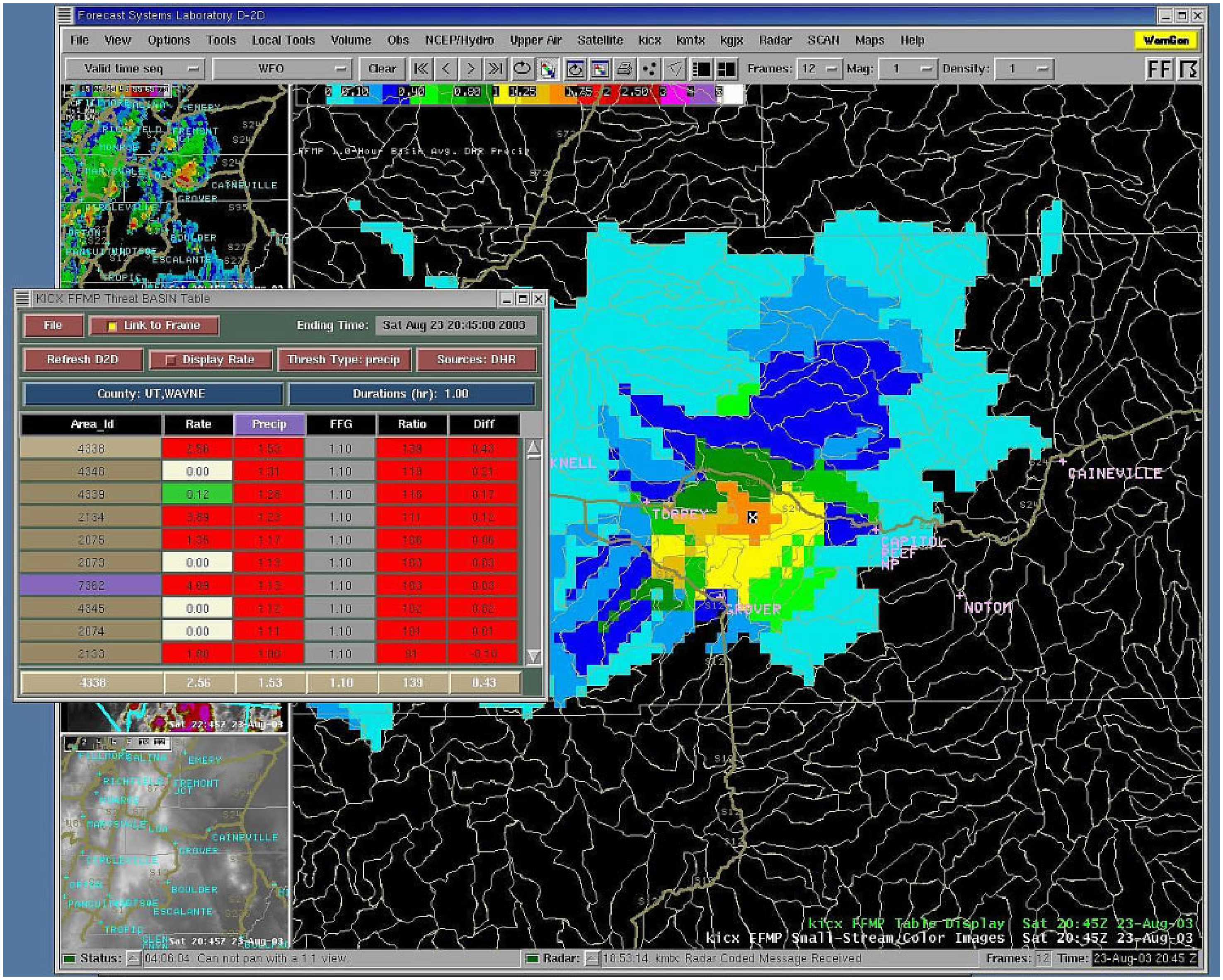

Forecast Systems Laboratory D-2D
File View Options Tools Local Tools Volume Obs NCEP/Hydro Upper Air Satellite kicx kmtx kgjx Radar SCAN Maps Help
WarnGen
Valid time seq
WFO
Clear
Frames: 12
Mag: 1
Density: 1
FFMP 1.0-Hour Basin Avg. DHR Precip
KICX FFMP Threat BASIN Table
File
Link to Frame
Ending Time: Sat Aug 23 20:45:00 2003
Refresh D2D
Display Rate
Thresh Type: precip
Sources: DHR
County: UT,WAYNE
Durations (hr): 1.00
Area_Id Rate Precip FFG Ratio Diff
4338 2.56 1.53 1.10 139 0.43
4340 0.00 1.31 1.10 119 0.21
4339 0.12 1.28 1.10 116 0.17
2134 3.89 1.23 1.10 111 0.12
2075 1.35 1.17 1.10 106 0.06
2073 0.00 1.13 1.10 103 0.03
7362 4.89 1.13 1.10 103 0.03
4345 0.00 1.12 1.10 102 0.02
2074 0.00 1.11 1.10 101 0.01
2133 1.80 1.00 1.10 91 -0.10
4338 2.56 1.53 1.10 139 0.43
KNELL
TORREY
CAINEVILLE
CAPITOL REEF NP
GROVER
NOTOM
kicx FFMP Table Display Sat 20:45Z 23-Aug-03
kicx FFMP Small-Stream Color Images Sat 20:45Z 23-Aug-03
Status: 04:06:04 Can not pan with a 1:1 view.
Radar: 18:53:14 kmtx Radar Coded Message Received
Frames: 12 Time: 23-Aug-03 20:45 Z

Figure 14

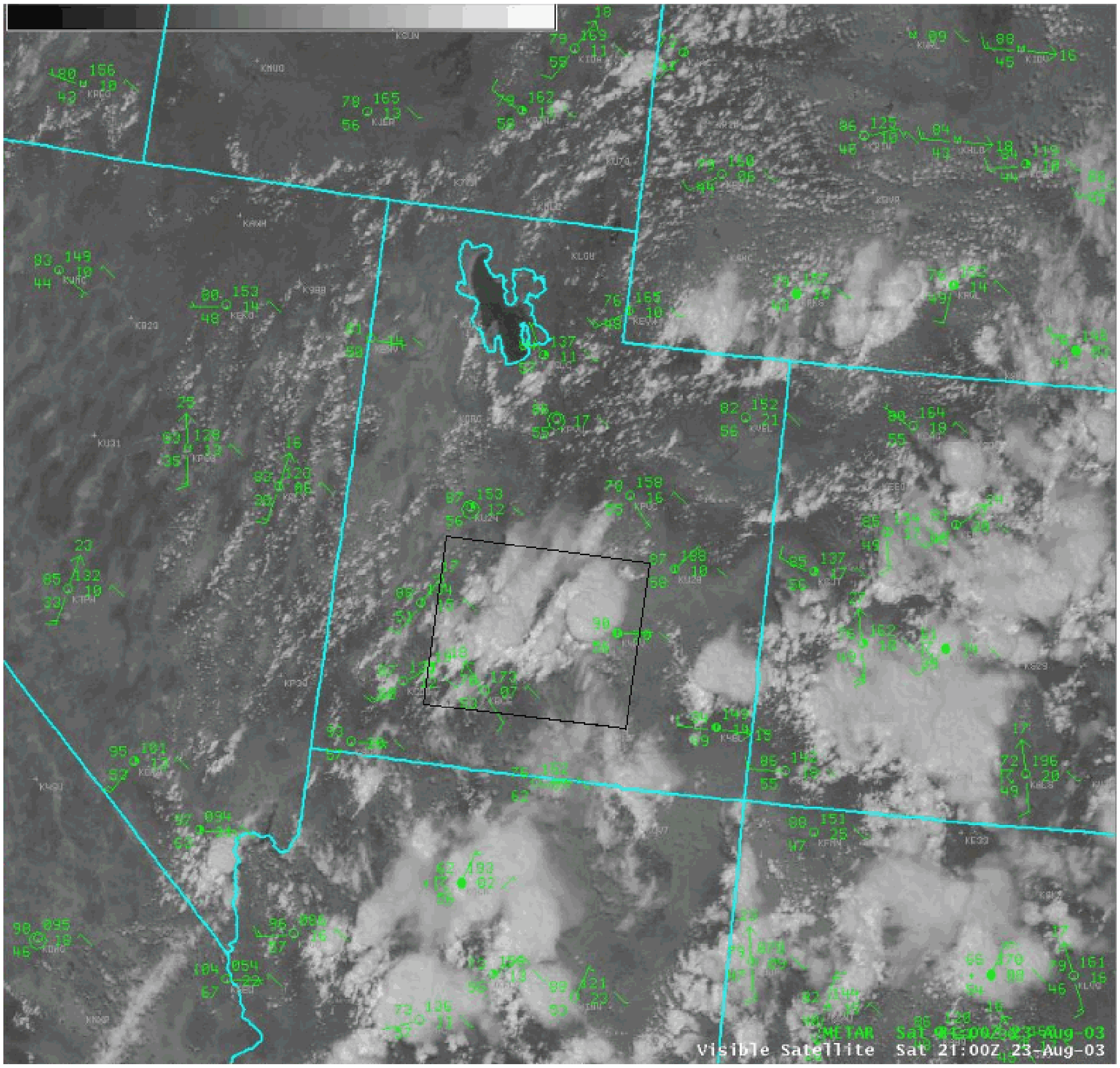
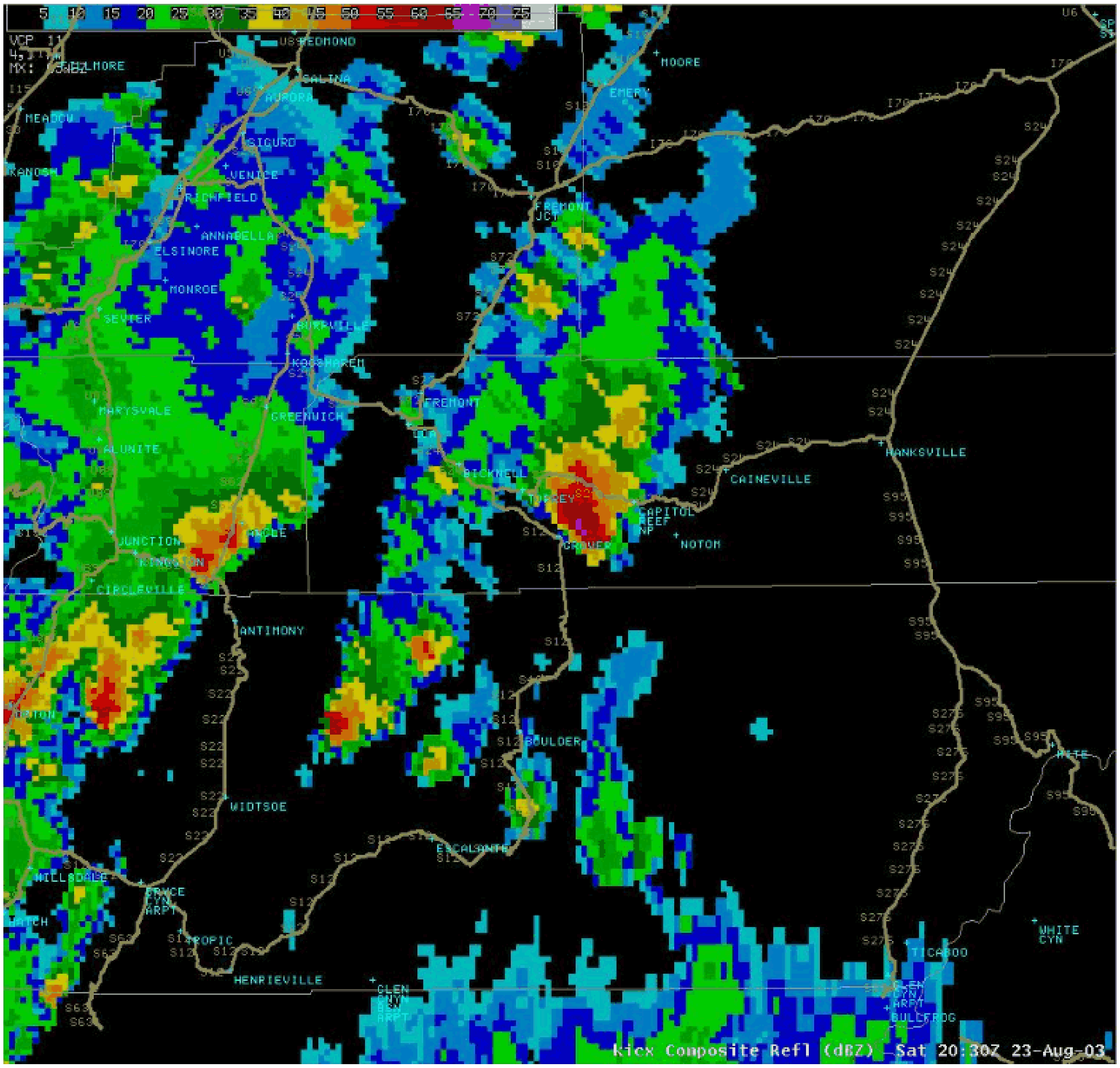
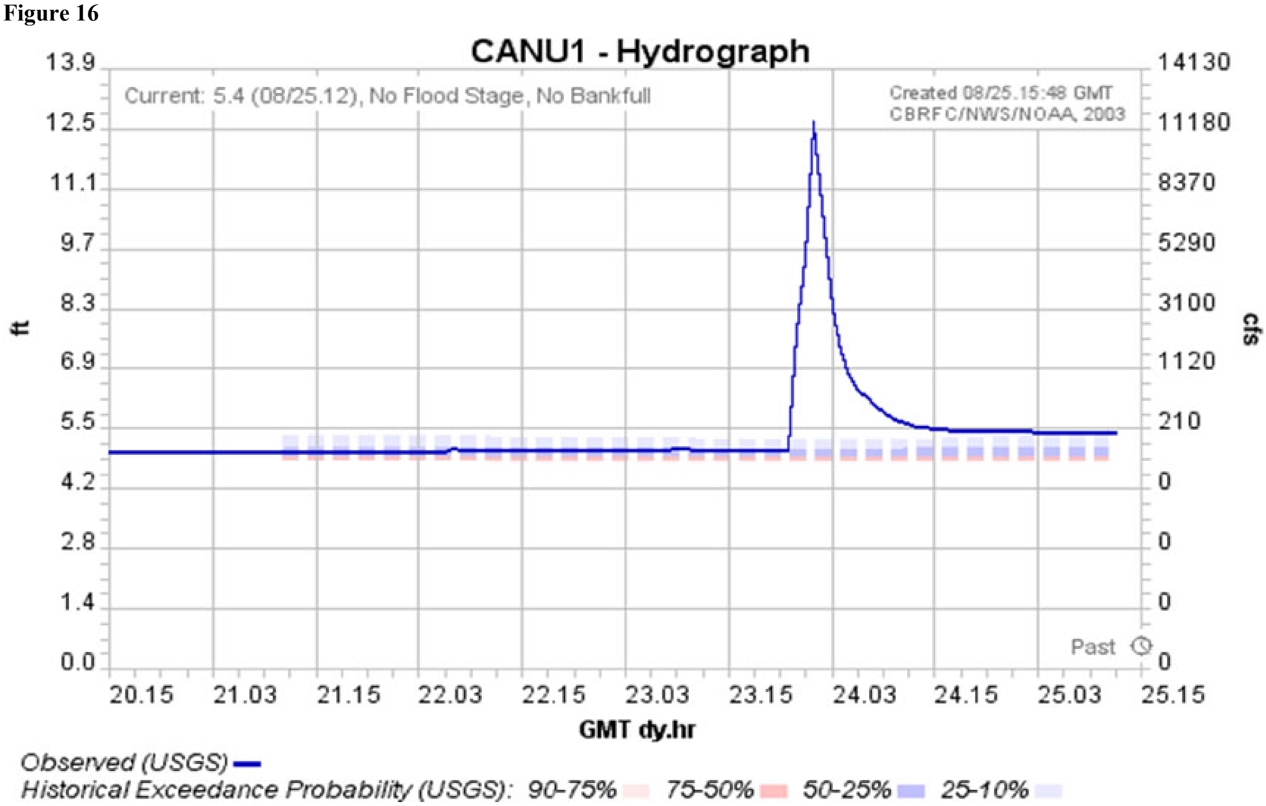


Figure 15



5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
REDMOND
SALINA
AURORA
SIGURD
VENICE
RICHFIELD
ANNABELLA
ELSINORE
MONROE
SEVIER
KOOSHAREM
GREENWICH
MARYSVALE
ALUNITE
JUNCTION
KINGSTON
CIRCLEVILLE
ANTIMONY
WIDTSOE
BRYCE CYN ARPT
TROPIC
HENRIEVILLE
ESCALANTE
BOULDER
FREMONT
FREMONT JCT
MOORE
EMERY
BICKNELL
TORREY
GROVER
CAPITOL REEF NP
NOTOM
CAINEVILLE
HANKSVILLE
TICABOO
WHITE CYN
BULLFROG
Kicx Composite Refl (dBZ) Sat 20:30Z 23-Aug-03

Figure 16



CANU1 - Hydrograph
Current: 5.4 (08/25.12), No Flood Stage, No Bankfull
Created 08/25.15:48 GMT
CBRFC/NWS/NOAA, 2003
ft
13.9
12.5
11.1
9.7
8.3
6.9
5.5
4.2
2.8
1.4
0.0
cfs
14130
11180
8370
5290
3100
1120
210
0
0
0
0
Past
20.15
21.03
21.15
22.03
22.15
23.03
23.15
24.03
24.15
25.03
25.15
GMT dy.hr
Observed (USGS)
Historical Exceedance Probability (USGS): 90-75% 75-50% 50-25% 25-10%

Figure 17

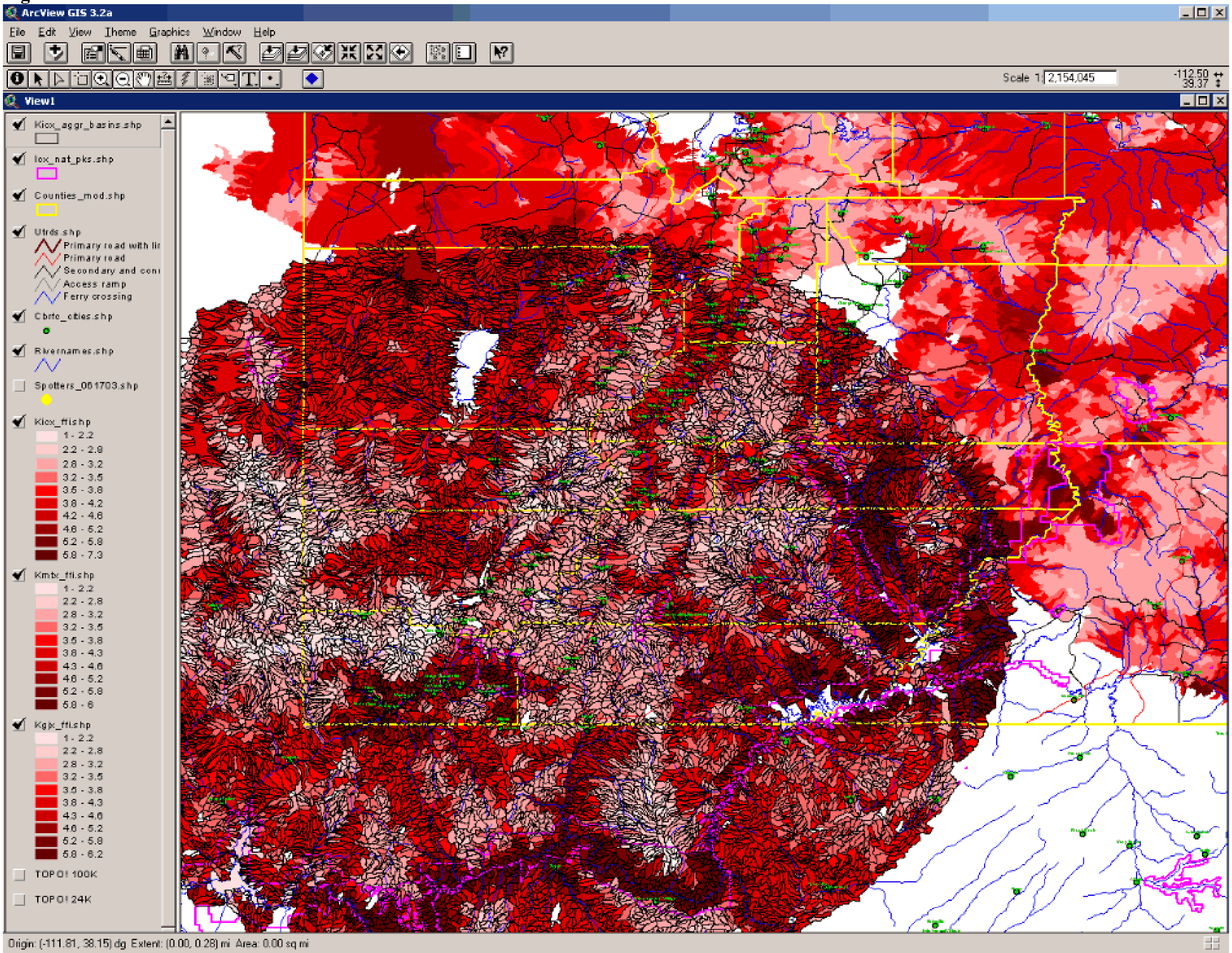
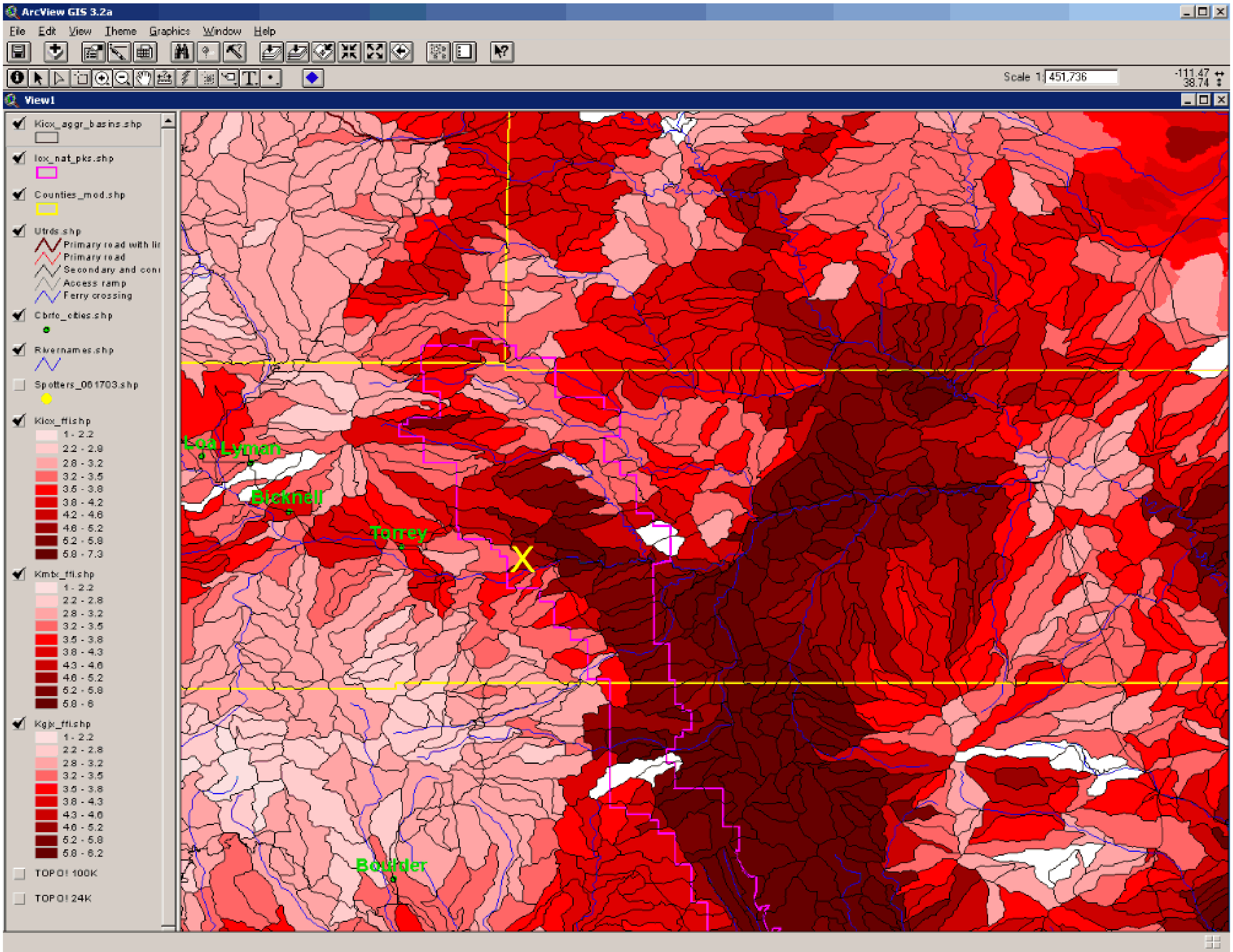


Figure 18


ArcView GIS 3.2a
File Edit View Theme Graphics Window Help
Scale 1: 451,736
-111.47
38.74
View1
Kicx_aggr_basins.shp
Iox_nat_pks.shp
Counties_mod.shp
Utrds.shp
Primary road with lir
Primary road
Secondary and conr
Access ramp
Ferry crossing
Cbrfc_cities.shp
Rivernames.shp
Spotters_061703.shp
Kicx_ffi.shp
1 - 2.2
2.2 - 2.8
2.8 - 3.2
3.2 - 3.5
3.5 - 3.8
3.8 - 4.2
4.2 - 4.6
4.6 - 5.2
5.2 - 5.8
5.8 - 7.3
Kmtx_ffi.shp
1 - 2.2
2.2 - 2.8
2.8 - 3.2
3.2 - 3.5
3.5 - 3.8
3.8 - 4.3
4.3 - 4.6
4.6 - 5.2
5.2 - 5.8
5.8 - 6
Kgjx_ffi.shp
1 - 2.2
2.2 - 2.8
2.8 - 3.2
3.2 - 3.5
3.5 - 3.8
3.8 - 4.3
4.3 - 4.6
4.6 - 5.2
5.2 - 5.8
5.8 - 6.2
TOPO! 100K
TOPO! 24K
Loa
Lyman
Bicknell
Torrey
X
Boulder