WESTERN REGION TECHNICAL ATTACHMENT
NO. 02-12
September 24, 2002

RAINFALL EVENTS AND THEIR EFFECT ON SEVERELY BURNED AREAS OF WESTERN MONTANA FOLLOWING THE FOREST FIRES OF 2000

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Introduction

Forest fires that occurred in the summer of 2000 burned large tracts of land in western Montana. Approximately 356,000 acres of forested land were burned in the mountains surrounding the southern end of the Bitterroot Valley, with many rural residents losing homes to the flames (Fig.1). Once the fires had dissipated the first week of September, the focus turned to possible flood threats in the rural residential interface. Many homes that survived the fires and new homes being built next to the burned areas were at risk of being flooded. Small watersheds in the Bitterroot National Forest had soils that were altered by high intensity forest fire and this left the landscape susceptible to increased runoff. Laird Creek and North Fork Rye Creek were two watersheds where the residential interface was at a high risk of flooding. Laird Creek is a small tributary of the East Fork of the Bitterroot River near the town of Sula, Montana, and North Fork Rye Creek feeds Rye Creek which enters the Bitterroot River between the towns of Conner and Darby, Montana. United States Forest Service (USFS) mapping of the watersheds indicated high intensity burn severity across some portion of these drainages. This type of burn left the hillsides void of vegetation and duff layers which intercept and absorb precipitation. A series of precipitation events occurred across the watersheds over the next water year (October 2000 - September 2001). Long duration rainfall events caused little runoff from the watersheds while high intensity, short duration storms caused flash flooding. The comparison of precipitation events and their effect on the watersheds is the focus of this paper.

Watershed Characteristics

Laird Creek is a perennial stream which drains from the southern end of the Bitterroot Mountains on the Bitterroot National Forest. The watershed has a drainage area of 9.3 mi^2 and flows into the East Fork of the Bitterroot River approximately 4.85 mi downstream of Sula, Montana. The forest is mainly comprised of Douglas-fir and ponderosa pine. Stands of Douglas-fir are noticed on all slopes and aspects from the lowest elevations to the highest peaks, while ponderosa pine are primarily on south facing aspects and exist in the elevation range of 4,300 ft to 6,800 ft. The mountains were formed by the intrusion of the Idaho batholith and the underlying geology is predominantly tertiary granite. Some hyperabyssal intrusive flows can be noticed at higher elevations and quaternary alluvium deposits closer to the basin outlet. The underlying granite has been weathered and the predominant soil type is granitic. Topography in the watershed ranges from 4,245 ft at the basin outlet to a high of 8,409 ft at Medicine point. Hillside slopes have extremes of 36 percent in the heavily timbered middle elevations and gentler 5 percent slopes in the alluvial deposits at lower elevations.

North Fork Rye Creek is also a perennial stream that flows into Rye Creek and eventually reaches the Bitterroot River near Highway 93, approximately 5 miles upstream of Darby, Montana. The watershed is predominantly forested and has a size of 18.4 mi^2. The majority of the trees in the watershed are Douglas-fir that comprise 75 percent of the forest with lodgepole pine, ponderosa pine and sub-alpine fir representing the rest. Topography was formed by the Idaho batholith intrusion and underlying geology consists of cretaceous granitic diorite and Precambrian metamorphic gneiss in the higher ridge line elevations. Elevations range from 4,232 ft at the basin outlet to 7,284 ft at the highest point, which is Deer Mountain. Most slopes have a gradient of 15-18 percent with some 37 percent grades, which leave some sections of the watershed susceptible to flashier runoff response.

Data Sources

In April 2001, the United States Geological Survey (USGS), USFS and National Weather Service (NWS) installed precipitation gauges in various watersheds of the Bitterroot National Forest to record rainfall data (Fig. 2). In order to determine stream discharge and height in the Laird Creek watershed, a river gage with recording devices was established at the basin outlet (Fig. 3). Data was recorded every 5 minutes and stored on a computer chip for later data retrieval. The NWS also attached a Handar 750A data collection platform to the co-located river and tipping bucket precipitation gage. Precipitation and stream gage height data were collected in real-time via a phone line that was interrogated every one-half hour from a personal computer at the NWS office in Missoula, Montana. A crest stage gage was installed in the North Fork Rye Creek watershed to capture peak flow heights and a tipping bucket precipitation gage was also installed in the middle of the basin. The USFS installed a Remote Automated Weather Site (RAWS) that collects meteorological data, including rainfall data every hour. This data was transmitted real time via Geostationary Orbiting Environmental Satellite (GOES) telemetry to the NWS office in Missoula, Montana. Data from these locations was used to evaluate the frequency of precipitation events and their affect on runoff from the burn areas. The NWS Doppler Radar estimates were also compared to data from the precipitation gauges.

Forest Fire Burn Severity

The burn severity areas of the Bitterroot National Forest were mapped by USFS hydrologists and soil scientists from helicopter reconnaissance and verified by ground visits (Fig. 4). Fire severity is a qualitative measure of fire effects on a component of the ecosystem (Robichaud 1997) and the burn severity mapping done in the Bitterroots was based on guidelines developed by the USFS. These guidelines are defined in the USFS Handbook Series 2509.13 under the section of burned-area emergency rehabilitation.

High Burn Severity Definition

A high intensity burn area is determined when 40 percent or more of the area exhibits the following characteristics:

1. Ashes are white or reddish color, indicating that much of the carbon was oxidized by the fire, especially if they are over 2 inches in depth. This consistently indicates zones of intensive burn with long residence time.

2. When fuels greater than 0.75 inches in diameter and more than 80 percent of the plant canopy have been consumed.

3. Litter is totally consumed with only a few ashes remaining on the soil surface.

4. Plant root crowns of sprouting brush and grasses are consumed or heavily damaged by the fire.

5. The soil surface is crusted or baked.

Medium Burn Severity Definition

A medium intensity burn area is determined when less than 40 percent of the area exhibits high burn severity and the following characteristics:

1. Sparse ashes that are darker in color.

2. When fuels 0.5 inches in diameter and 60 percent of the plant canopy have been consumed.

3. Litter is charred but not ashed.

Low Burn Severity Definition

A low intensity burn area is determined when moderate or low-intensity characteristics are met on the entire area:

1. Sparse ashes that are darker in color.

2. When fuels up to 0.25 inches in diameter and less than 40 percent of the brush canopy have been consumed.

3. Litter has only been singed.

High Intensity Burn Effect on Vegetation and Soils

An analysis of the predominant vegetation and soils in the high burn severity areas of the Laird and North Fork Rye Creek watersheds was completed in order to determine how the loss or change of each component would affect watershed response. Analysis of Geographic Information System (GIS) spatial layers obtained from the USFS indicated the following:

1. 70-75 percent of the high burn severity occurred on forest associated with Douglas-fir habitat, 17 percent in ponderosa pine stands and the remaining 10 percent occurred on small tracts of lodgepole pine and sub-alpine fir.

2. The predominant soil classification throughout the watersheds in the high burn severity areas consists of sandy to loamy, mixed cryochrepts and loamy-skeletol ustochrepts. Both of which, are highly erosive in steep slopes, and contain relatively shallow soil horizons.

No correlation could be determined between different tree species and their affect on runoff, however, the loss of tree canopy and duff layers associated with the species had an affect on runoff and erosion. The total amount of interception by trees, shrubs, grasses and duff layer can add up to a significant amount as studied by Helvey and Zinke. The amount of water required to wet the vegetation (average rainfall storage values) ranges from 0.013 inches to 0.09 inches for coniferous and hardwood forests of the United States, according to a review by Helvey (1971) (Tiedemann et al.). A summary by Zinke (1967) showed that interception by shrubs and grasses averages .05 inches and that storage values on the forest floor average about 0.16 inches (Tiedemann, et al.).

No field tests of soils were conducted by the authors to determine if hydrophobicity existed, however, the relationship between intense heating of soil and associated hydrophobicity is well documented by DeBano (1981). Any mineral soil containing more than a couple of percents of organic matter is likely to become water repellent to some degree when heated (DeBano 1981). Studies by Megahan and Militor (1975), reported sheet erosion and rilling on granitic soils in Idaho were both greatly accelerated following a wildfire on a clearcut area of mixed Douglas-fir and ponderosa pine (Tiedeman, et al.). It stands to reason that some hydrophobicity should exist in the high burn severity areas of the Bitterroot Watersheds considering the effects that intense heating has on soils.

Rainfall Thresholds

Rainfall threshold rates for high burn severity areas of the Bitterroot National Forest had been established by the NWS in Missoula, Montana, prior to the summer of 2001. The rainfall threshold rate being used to predict flash flooding was 0.25 inches in less than an hour. The threshold value was established by investigations of long-duration and short-duration rainfall events that occurred in the fall months of September and October 2000. Raingage data from USFS RAWS and NWS cooperative observers, along with NWS Doppler Radar data were analyzed. The most conclusive data came from the Pardee Creek RAWS located in the Lolo National Forest near the town of Superior, Montana. In September 2000, a rainfall event occurred over a forest fire burn area known as the Thompson Flat Complex near Superior. In that event, 24-hour storm total rainfall of 0.60 inches was measured with 0.20 inches occurring in less than an hour. A subsequent investigation of the area by the authors revealed flash flooding and debris flow from a high burn severity section of the fire complex.

Weather Background

The southern Bitterroot Valley in southwest Montana averages between 30 and 50 thunderstorm days a year (Fig. 5) and is the most active convective area in the Weather Forecast Office (WFO) Missoula County warning area (CWA). According to *Storm Data*, Ravalli County in southwest Montana averages one severe thunderstorm event each year with data heavily weighted by weather spotter reports in the Bitterroot Valley. In 2001, the WFO Missoula CWA had a total of 21 severe events, one of which occurred in Ravalli County. In addition, no severe thunderstorms were recorded during the three flash flood events mentioned in this paper.

There is a higher frequency of thunderstorms in southwest Montana compared to the rest of western Montana mainly because of the steep mountainous terrain, ranging from roughly 7,000 ft to over 10,000 ft peaks, high elevated valleys, and the occasional presence of monsoon moisture during the summer months. A strong four-corners high pressure system in the upper atmosphere and low pressure trough along the west coast, results in south to southwesterly winds aloft over the Pacific Northwest and northern Rockies. This wind pattern moves monsoon moisture, originating from the desert Southwest of the United States and Old Mexico, northward across the Great Basin and into southwest Montana.

Strong afternoon surface heating during a summer day and a layer of mid-level moisture can lead to development of convection in updrafts near mountain ridges. A shortwave trough and/or a jet streak in the upper atmosphere can help organize thunderstorms into longer-lived single or multiple cells that are more likely to move out across valley areas. Usually, thunderstorms in western Montana are pulse-type events lasting less than an hour.

Doppler Radar Considerations

The WFO Missoula Doppler Radar (KMSX) is located on Point Six Mountain, approximately 8 nm north of the WFO Missoula office at an elevation of 8,039 ft MSL. The vast majority of the severely burned areas of 2000 are located roughly 70 nm to the south of the radar near the town of Sula, at 5,160 ft MSL. The lowest elevation scan (0.5° tilt) of the KMSX radar beam at this distance is at an elevation of 15,700 ft MSL.

The elevated radar site of KMSX presents numerous problems with data quality and availability at farther distances from the radar. In all flash flood events that occurred in July 2001, the freezing level was between 11,000 ft and 14,000 ft MSL. The freezing level was below the lowest elevation scan of the radar beam 15,700 ft at this distance. Therefore, the Doppler sampled data is derived mainly of graupel and supercooled water droplets caught in thunderstorm updrafts. In each thunderstorm cell near Sula, the radar detected the maximum reflectivity at the level of the lowest elevation scan 15,700 ft (Fig. 6). It was therefore unknown if stronger reflectivity returns occurred or extended well below the radar beam since the storm centroid elevation was unavailable. If we look at an earlier radar scan shown at a larger viewing angle (Fig. 7), cell Z4 is stronger than cell X5 and positioned closer to the radar. However, the maximum reflectivity of cell Z4 (64 dbZ) occurred at the lowest elevation scan and, therefore, could be more intense below the radar beam as well. The inability of KMSX radar to detect significant reflectivities at lower elevations likely creates a trickle-down effect on the Doppler precipitation processing algorithms for generation of the 1-hour precipitation estimate (OHP). Further study beyond the scope of this research paper could shed light on the significance of the OHP at elevated radar sites in the Western United States.

The single-cell thunderstorms that moved over the severely burned watersheds from 15 July 2001 through 21 July 2001 were high intensity, short duration precipitation (Egger and Vasiloff 1998) events, generally lasting no more than 30 minutes. Doppler OHP estimates are based on 1-hour increments. This time lag associated with the OHP means the precipitation processing algorithm is continuously "catching-up" with actual storm activity by adding previous radar scans and time-averaging to formulate the OHP product. Given the quick runoff reaction of a burned forest in steep terrain, the OHP was not helpful in real-time since the flash flooding was already occurring by the time the radar indicated the heaviest rainfall. However, the OHP was useful in evaluation of upstream rainfall estimates prior to reaching the burned area, and provided a storm track history.

The OHP gave varying results depending on the type of storm event compared to the recorded amounts in the rain gauge network (ground truth) near the burned areas. Two flash flood events, 15 July 2001 and 21 July 2001, were noted for their significant hail content with storm spotter reports of hail accumulations of one to two inches in depth. Radar reflectivity of thunderstorm cells ranged from 60-65 dbZ, along with Vertically Integrated Liquid (VIL) values of 30-40 kg m $^{-2}$ with these events. Some rainfall overestimation seemed likely, but comparison between radar estimates and rain gauges showed fairly similar precipitation amounts. The flash flood event of 20 July 2001 did not include significant hail due to lower-topped thunderstorm cells, with peak reflectivities of 50-55 dbZ and VIL less than 20 kg m^{-2}. The OHP estimates were lower than the other events as expected; however, rain gauge amounts lead to the conclusion that the OHP was underdone in this case. Rain gauges detected 0.4 inch amounts in the Laird Creek basin, which occurred in about a 30 minute time frame. The OHP showed an amount of 0.4 inches, but should have been closer to 0.8 inches per hour.

Radar OHP estimates give limited assistance during a flash flood event on severely burned areas located in steep terrain. Establishing a history of rainfall intensity and storm motion from prior storm cells are benefits, but lag time is too great to give real-time assistance of precipitation accumulation during a flash flood event. An analysis of precipitation data in smaller time increments for small watersheds, like available in AWIPS software upgrades containing the Area Mean Basin Estimated Rainfall (AMBER) system, would benefit forecasters by providing estimated precipitation data close to real-time.

Flash Flood Overview

Weather patterns during all flash flood events were reflections of typical synoptic conditions for the summer season in western Montana, with low pressure across the eastern Pacific Ocean and high pressure over the southern Rockies. Although southwest Montana averages many more thunderstorm days (Fig. 5) when compared to the rest of the WFO Missoula CWA, there was nothing unusual about the 2001 convective season. The only outlying factor during each episode that was not "normal" was a relatively high total precipitable water (TPW) value. The TPW (Huschke, Glossary of Meteorology) is the total atmosphere water vapor contained in a column of unit cross-section extending all the way from the earth's surface to the "top" of the atmosphere. There is a general correlation between precipitation amounts in given thunderstorms and the precipitable water vapor of the air masses involved in those storms. A normal TPW value in western Montana is approximately 0.50 inches during the summer months (data provided by NOAA-CIRES Climate Diagnostics Center), but can often be closer to 0.30 inches during a extended dry period of approximately a week or more. Summer weather patterns more typically bring dry, mid-level Pacific air across southwest Montana, resulting in dry, sub-cloud layers and inverted-v sounding signatures. The TPW values greater than 0.50 inches during July 2001 indicated a potential to more easily saturate water vapor in the low levels of the atmosphere, resulting in minimal evaporation and good precipitation efficiency (Doswell et al. 1996) during convection.

Forecasters should be aware of favorable conditions for wet thunderstorm development over their CWA, similar to the events that occurred in southwest Montana during July 2001. A saturated air mass with above normal TPW values will result in better accuracy of the OHP estimates and less overestimation, which might occur as a result of dry air in the lower layers below convective cloud bases. Also, storm motion generally less than 20 mph was adequate to achieve heavy rainfall in these flash flood events.

The following is a review of the flash flood cases of 15 July, 20 July and 21 July 2001, including the synoptic weather pattern for each event that lead to heavy rainfall and eventual flooding, satellite pictures near the time of flash flooding, select ETA model data, and evaluation of the KMSX Doppler Radar performance.

Flash Flood Event - 15 July 2001

On 15 July 2001, upper level low pressure resided over the southwest corner of British Columbia (Fig. 8), resulting in a southwesterly flow aloft over the WFO Missoula CWA, which is a favorable pattern for thunderstorm development. In the afternoon, a weak shortwave and a 80 kt jet speed maxima were across western Montana (Fig. 9). The best region of upper level divergence was positioned over southwest Montana and the 12-hour ETA model sounding for Hamilton (HMM), Montana, valid 0000 UTC 16 July 2001 (Fig. 10) indicated steep lapse rates and buoyancy available. The TPW values were well above normal according to the ETA model with values from 0.6 to 0.8 inches.

As in most summer afternoons with favorable convective potential for western Montana, the location where thunderstorms will form is difficult to pinpoint at best. Given the high TPW in the region on 15 July 2001 (Fig. 9) and storm motion less than 20 mph, heavy rainfall was possible in the CWA. By 2:00 pm MDT (2000 UTC), thunderstorms developed rapidly southwest of Sula and began to move over burned watersheds of southwest Montana. Flash flooding occurred between 2030 UTC and 2230 UTC as thunderstorms crossed over the North Fork Rye Creek watershed.

Doppler Radar detected maximum reflectivities of 60 dbZ during the flash flood event with VIL of 30-35 kg m $^{-2}$. Storm spotters reported small hail, generally less than 0.5 inches, associated with VIL of this value. A hand-drawn analysis of the radar's storm total estimate superimposed over terrain and southwest Montana river basins (Fig. 11 and Table 4 in the "Appendix") shows relatively accurate precipitation estimates during the event when compared to the rain gauge network or ground truth.

The subsequent runoff from the high burn severity areas created flash flooding which washed out many roads and flooded homes at the base of normally dry draws. Rainfall data from a USGS tipping bucket gage in the middle of the watershed indicated 0.56 inches in 30 minutes and a USFS RAWS at the top of the drainage reported 0.29 inches for a 1 hour time span. A frequency analysis of the precipitation data was performed by the USGS and a recurrence interval of 5-10 years was determined for the storm; however, an indirect discharge measurement and subsequent frequency analysis of the flood flow data produced a recurrence interval of 100 years. These analyses provide insight to the potential of extreme runoff from high severity burn areas when hit with typical summer thunderstorm rains.

Flash Flood Event - 20 July 2001

A similar convective weather pattern was in place on 20 July 2001. A cold-core upper low over western Oregon (Fig. 12) was supplying strong divergence aloft over the Northern Rockies. Once again, a weak shortwave aloft spun off the upper low (Fig. 13) and 80 kt winds at 250 mb moved over the burned area helping to initiate afternoon convection. The

TPW values remained above normal during this event, with values from 0.6 to 0.8 inches. The sounding for HMM indicated steep 700-500 mb lapse rates of 7.4°C km^{-1} and weak speed shear aloft(Fig. 14). Thunderstorms erupted by midday across Idaho and moved into southwest Montana around 1900 UTC, similar timing as in the 15 July 2001 case, with flash flooding occurring in the burned areas from 2000 UTC to 2200 UTC.

Doppler Radar detected maximum reflectivities of 51 dbZ during the event with VIL of 15-20 kg m^{-2}. Some hail was reported by spotters but thunderstorm cells were weaker than in the other flash flood events. The OHP estimates showed a maximum of 0.4 inches which was underdone when compared to the rain gauge network. Radar precipitation estimates should be about double those found in (Fig. 15) to match ground truth(Table 5 in the "Appendix") since the rainfall lasted about 30 minutes. Rainfall recorded at the USGS tipping bucket raingage at the mouth of Laird Creek reported 0.42 inches in a 30-minute time span (Fig. 16). The resulting flood hydrograph from the USGS River gauge at the same location reported a 6.5 ft rise in 30 minutes with a peak of 8.58 ft. The flood wave exceeded the capacity of the 48 inch culvert at Highway 93 and overtopped the road. Travel between Idaho and Montana was temporarily shutdown to remove debris from the highway. The NWS and USGS frequency analysis on the storm revealed a recurrence interval of 5-10 years, while the USGS frequency analysis of the resulting flood flow indicated a 500-year recurrence interval (Fig. 16). The frequency analysis clearly indicates that the previous year's fire had altered the runoff potential of the Laird Creek Watershed.

Flash Flood Event - 21 July 2001

Very little had changed in the synoptic pattern on 21 July 2001 from the previous day. A southwesterly jet remained over the region while the upper low had moved from western Oregon to central Washington. Weak shortwaves continued to rotate over southwest Montana with good upper divergence and steep lapse rates predicted by the 1200 UTC ETA model run. Residual low-level moisture from the previous day's thunderstorms contributed to a slower climb in afternoon temperatures over the area, therefore, convection was not initiated until later in the day. Thunderstorms developed across Idaho before 5:00 pm MDT (2300 UTC) and moved into southwest Montana by 2330 UTC. Flash flooding occurred across southwest Montana between 2300 UTC 21 July 2001 and 0200 UTC 22 July 2001 as strong, single-cell thunderstorms moved northward at 20 mph across numerous burned watersheds (Figs. 6 and 7).

Doppler Radar detected stronger cells than on 20 July 2001 with maximum reflectivities of 60-65 dbZ and VIL of 30-35 kg m^{-2}. The OHP maximum (Fig. 17 and Table 5 in the "Appendix") exceeding 1.5 inches was deemed fairly accurate (30-minute storm rainfall total compared to the previous day's event) considering the high reflectivity values and numerous spotter reports of 0.5 inch hail covering the ground up to 2 inches in depth. Data collected from the rainfall and river gauges showed a rain and flood event that was similar to the one that occurred on the 20th (Fig. 18). The 30-minute storm total on the 21st produced 0.54 inches of rain, which was 0.12 inches more than the July 20 event. The NWS and USGS rainfall frequency analysis showed a recurrence interval of 10-25 years for the July 21 storm. The resulting hydrograph had to be reconstructed using 30-minute data from the NWS telemetry device due to a failure in the USGS 5-minute data recorder (Fig. 18). The USGS indirect discharge measurements and flood frequency analysis indicated a flow of 230 cfs which was slightly greater than a 500-year recurrence interval.

Non-Flash Flood Event - 29-31 July 2001

A longer duration rain event hit the watershed approximately 1 week later on 29 July through 31 July 2001. An upper level trough matured to a closed low pressure system over southwest Montana on 30 July 2001. This system cooled temperatures below normal with periods of heavier showers and embedded low-topped thunderstorms impacting the burned watersheds. Two day storm total rainfall from the event was an impressive 1.10 inches, although the resulting hydrograph showed only a 0.16 foot rise at the USGS river gauge (Fig. 19). An analysis of the rainfall rates indicate heaviest amounts fell during the early morning of 31 July 2001, with 0.07 inches from 0000 MDT to 0030 MDT and 0.13 inches from 0030 MDT to 0100 MDT. This left a total of 0.20 inches for a 1-hour period compared to 0.44 inches and 0.54 inches that occurred in a 30-minute period on the 20th and 21st events.

This comparison indicates that the intensity and duration of the rain event is a more important component to producing flood flows than antecedent conditions. Rainfall associated with thunderstorms in the summer months typically produce high intensity, short duration events and a threshold rainfall rate appears to be needed before excessive runoff is generated. Longer duration rain events that do not meet the rainfall threshold do not produce abundant runoff, even when soils are saturated.

Rainfall Effect on Watershed Response

Rain that fell on 20 July 2001 and 21 July 2001 covered the entire Laird Creek watershed according to data collected from USGS tipping bucket precipitation gauges in the middle and outlet of the basin. Doppler Radar also indicated basin area coverage of precipitation (Figs. 15 and 17). The time to peak for the flood hydrographs on the 20th and 21st were 30 minutes (Figs. 16 and18). The observed time to peak(t_p) from the July 2001 floods differs with that of a computed t_p using Snyders method. A computed lag time and time to peak as determined by Snyders method using physiographic watershed characteristics can be seen below:

$t_1 = C_t(L_{ca}L)^{0.3}$

where t_1 = the lag time (hr) between the center of mass of the rainfall excess for a specified type of storm and the peak rate of flow
L_{ca} = the distance along the main stream from the base gauge to a point nearest the center of gravity of the basin (mi)
L = the maximum travel distance along the main stream (mi)
C_t = coefficient depending on the basin properties

and $C_t = 1.2$ $L = 5.793$ mi $L_{ca} = 2.579$ mi

$t_p = D/2 + t_1$

where t_p = the time from the beginning of rainfall to peak discharge (hr)

D = the duration of rainfall (hr)
t_1 = the lag time from the centroid of rainfall to peak discharge (hr)

and D = 30 min or 0.5 hr $t_1 = 2.70$ hr

The relative timing of hydrologic events must be known if drainage areas having sub-basins are to be modeled or if continuous simulation is desired (Viessman, Lewis and Knapp, 1989). A basic measure of timing is lag time or basin lag, which locates the hydrograph's position relative to the causative storm pattern (Fig. 20 fromViessman, Lewis and Knapp 1989). It is that property of a drainage area which is defined as the difference in time between the center of mass of effective rainfall and the center of mass of runoff produced (Viessman, Lewis and Knapp 1989). Time lag is characterized by the ratio of a flow length to a mean velocity of flow and is, thus, a property that is influenced by the shape of the drainage area, the slope of the main channel, channel geometry, and storm pattern (Viessman, Lewis and Knapp 1989).

The difference in time to peak between Snyders method (2.95 hrs) and the observed value from the river gauge hydrograph (one-half hour) can be explained by analyzing the high intensity burn areas and their close proximity to the river gauge outlet. A large percentage of high intensity burn was near the basin outlet, which produced the majority of the excessive runoff that affected the timing of the hydrograph. A field inspection by the authors revealed large volumes of flows from high burn severity areas in the draws of the lower portion of the watershed and insignificant runoff from areas of medium and low burn severity throughout the watershed (Fig. 4).

Precipitation Frequency Analysis

Precipitation frequencies with 24-hour and 6-hour durations are plotted for the State of Montana in the NOAA ATLAS 2 (Precipitation-Frequency Atlas of the Western United States - Volume I-Montana). Rain events that occurred on 20 July 2001 and 21 July 2001 were of 30-minute durations and could not be obtained from the NOAA ATLAS 2 maps, therefore, these values had to be derived from procedures defined in the NOAA ATLAS 2 publication. A 1-hour value of 1.06 inches and 0.39 inches were determined for the 100 and 2 year storm events, respectively, using the following equations:

100 yr 1-hr value $\boxed{Y_{100} = 0.338 + 0.670[X_1(X_1/X_2)] + 0.001(X_3)}$

$X_1 = 1.80$ in X_1 = 100 yr 6-hr value
$X_2 = 3.00$ in X_2 = 100 yr 24-hr value
$X_3 = 42.45$ X_3 = elevation (in hundreds of feet)

$Y_{100} = 0.338 + 0.670[1.80(1.80/3.00)] + 0.001(42.45)$
$Y_{100} = 1.06$ in

2 yr 1-hr value $\boxed{Y_2 = 0.019 + 0.711[X_1(X_1/X_2)] + 0.001(X_3)}$

$X_1 = 0.80$ in $\quad X_1$ = 2 yr 6-hr value
$X_2 = 1.40$ in $\quad X_2$ = 2 yr 24-hr value
$X_3 = 42.45$ $\quad X_3$ = elevation (in hundreds of feet)

$Y_2 = 0.019 + 0.711[0.80(0.80/1.40)] + 0.001(42.45)$
$Y_2 = 0.39$ in

The Y_2 and Y_{100} values were then plotted on a nomogram (Fig. 21) and a straight line drawn between the two points. Values of the 5, 10, 25 and 50 year recurrence interval (Table 1) were then estimated from the nomogram (Fig. 21).

Table 1. One-hour precipitation values estimated from nomogram in Figure 20.

100yr 1-hr value = 1.06 in	10yr 1-hr value = 0.63 in
50yr 1-hr value = 0.88 in	5yr 1-hr value = 0.52 in
25yr 1-hr value = 0.77 in	2yr 1-hr value = 0.39 in

To obtain one-half hour precipitation frequency values, an adjustment factor needed to be applied to the 1-hour values (Table 1). The adjustment factor ratio table (Table 2) from NOAA ATLAS 2 was used to arrive at final estimates. Rainfall of 0.42 inches on the 20 July 2001 event was compared to one-half hour estimates (Table 3) to come up with a recurrence interval of 5-10 years. Likewise, the 0.54 inches from 21 July 2001 was determined to be a 10-25 year event.

Table 2. Adjustment factors to obtain *n*-minute estimates from 1-hr values

Duration (min)	5	10	15	30
Ratio to 1-hr	0.29	0.45	0.57	0.79

Table 3. Half-hour precipitation values derived from adjustment factors.

100yr ½-hr value = .83 in	10yr ½-hr value = 0.50 in
50yr ½-hr value = 0.69 in	5yr ½-hr value = 0.41 in
25yr ½-hr value = 0.61 in	2yr ½-hr value = 0.31 in

Flood Frequency Analysis

Following the rain events in July of 2001, the USGS conducted indirect discharge measurements in many of the watersheds of the Bitterroots. Peak flows on the North Fork

Rye Creek were determined to be 230 cfs from the rain event on 15 July 2001. Laird Creek had a computed flow of 205 cfs from the 20 July 2001 event and 230 cfs from the 21 July 2001 event. Provisional regression equations developed by Parrett (2001) were then used to arrive at a recurrence interval for the flows (Parrett, USGS, oral communication 2001).

Geomorphic Processes

Landscape Altering Geomorphic Processes

Many of the watersheds in the burned areas of the Bitterroot National Forest experienced geomorphic processes during high intensity rainfall events. Rill formation was common, especially at the headwaters of the draws that formed the watersheds. Hyperconcentrated flows and debris flows altered landscapes in many of the drainages and led to the formation of gullies and debris fans at the base of hillsides. These processes also added ash, mud, rock and trees to the flash flood flows that followed the thunderstorms.

Rills

Inspection of individual draws in the watershed revealed a series of rills that formed near ridgetops and steeper slopes as a result of intense rain impacting soils that were affected by high intensity fire (Fig. 22). Rill formation was more numerous on hill slopes in the upper elevations of the draws and transported water down the slopes into the center of the draws. Water then became concentrated in the draws and appears to have hyperconcentrated the flow, which led to gully erosion and formation (Fig. 23). Flows gathered erosive energy as they moved downslope and scoured gullies to granitic bedrock (Fig. 23). Tremendous amounts of soil, granitic boulders and trees were transported with the flows which deposited a large portion of their debris in debris fans at the confluence with perennial streams (Figs. 24 and 25).

Hyperconcentrated Flow and Debris Flow

Some questions arise as to the nature of the flows that formed gullies and led to flash flooding in the Bitterroot Watersheds. Were the flows hyperconcentrated flows or debris flows? Costa and Williams, 1984, reported that when poorly sorted soil and rock debris are mixed with a critical amount of water, a dense, structurally coherent slurry forms that can move rapidly down slopes and along channels causing great destruction. Debris flows resemble wet concrete and usually form as a result of hillslope failure during rainstorms (Costa and Williams 1984). Flood flows that occurred in the Laird and North Fork Rye Creek watersheds showed no visual evidence of hillslope failure which is commonly associated with debris flows; however, typical debris flow processes were found throughout the watersheds, such as:

- U-shaped gullies and gullies scoured to bedrock
- Larger clasts and boulders transported with the flow
- Debris fans at the base of gullies

Excessive runoff and debris transport from forest fires that have been studied by hydrologists with the USGS indicate the formation of debris flows as a process that typically occurs in high severity burn areas in the Western United States. Characteristics that indicate the formation of debris flows do not have to be associated with hillslope failure (Oral communication, Cannon and Parrett 2001).

Summary and Recommendations

Summary

The southern Bitterroot Valley and surrounding Bitterroot and Sapphire Mountains experience more thunderstorm events each year than any other area of the WFO Missoula CWA. Single-cell thunderstorms over southwest Montana, like those that occurred in July 2001, can lead to rapid runoff and flash flooding on severely burned watersheds. Under normal circumstances, this type of thunderstorm event would not lead to flooding. Radar performance was adequate to assist forecasters in the issuance of NWS flash flood warnings, however, OHP products were less than timely due to the flashy nature of burned soils located in steep terrain. Dry valley air is a common element during the summer months in southwest Montana. Elevated thunderstorms with virga and little rainfall occur frequently, leading to rainfall overestimation and faulty comparisons between Doppler OHP and ground truth. Above normal TPW values during the July 2001 flash flood events analyzed in this paper gave forecasters more confidence in radar performance and a heads up on potential flash flooding.

In the Laird and North Fork Rye Creek watersheds, roughly 30 percent of the basin was classified as high burn severity by the USFS. The high burn severity areas were determined to be the greatest threat to produce excessive runoff capable of flash flooding. These areas exhibited over 80 percent destruction of plant canopy and total incineration of the organic duff layer and baked soils lead to hydrophobic properties. The burned conditions altered watershed response leading to changes in time to peak for the watersheds. A derivation of time to peak using Snyders method based on basin characteristics indicated 2.70 hours to peak while observed stream-gauge data indicated a 30-minute time to peak.

Rainfall threshold rates that were developed and used by the NWS to predict flash flooding for the three events of July 2001 appeared to work well. However, threshold values that worked for predicting flooding one year after the fires may not work in preceding years. Rainfall should continue to be monitored at burn areas to see if threshold values change as the watersheds recover from forest fire.

Recommendations

Making contacts and working closely with other government agencies and local groups, such as the USFS, USGS, local law enforcement, county disaster and emergency managers, and recruiting volunteer citizens close to burned areas is key to a successful prediction and warning program. Consulting with government agencies in order to obtain additional precipitation and river gauge data in remote burn areas is critical to aiding meteorologists and hydrologists in predicting flash flooding. If forest fires occur on USFS land, it is important for NWS personnel to make contact with USFS hydrologists and soil scientists within a week or two after fires have ended in order to get involved in the Burn Area Emergency Rehabilitation (BAER) team.

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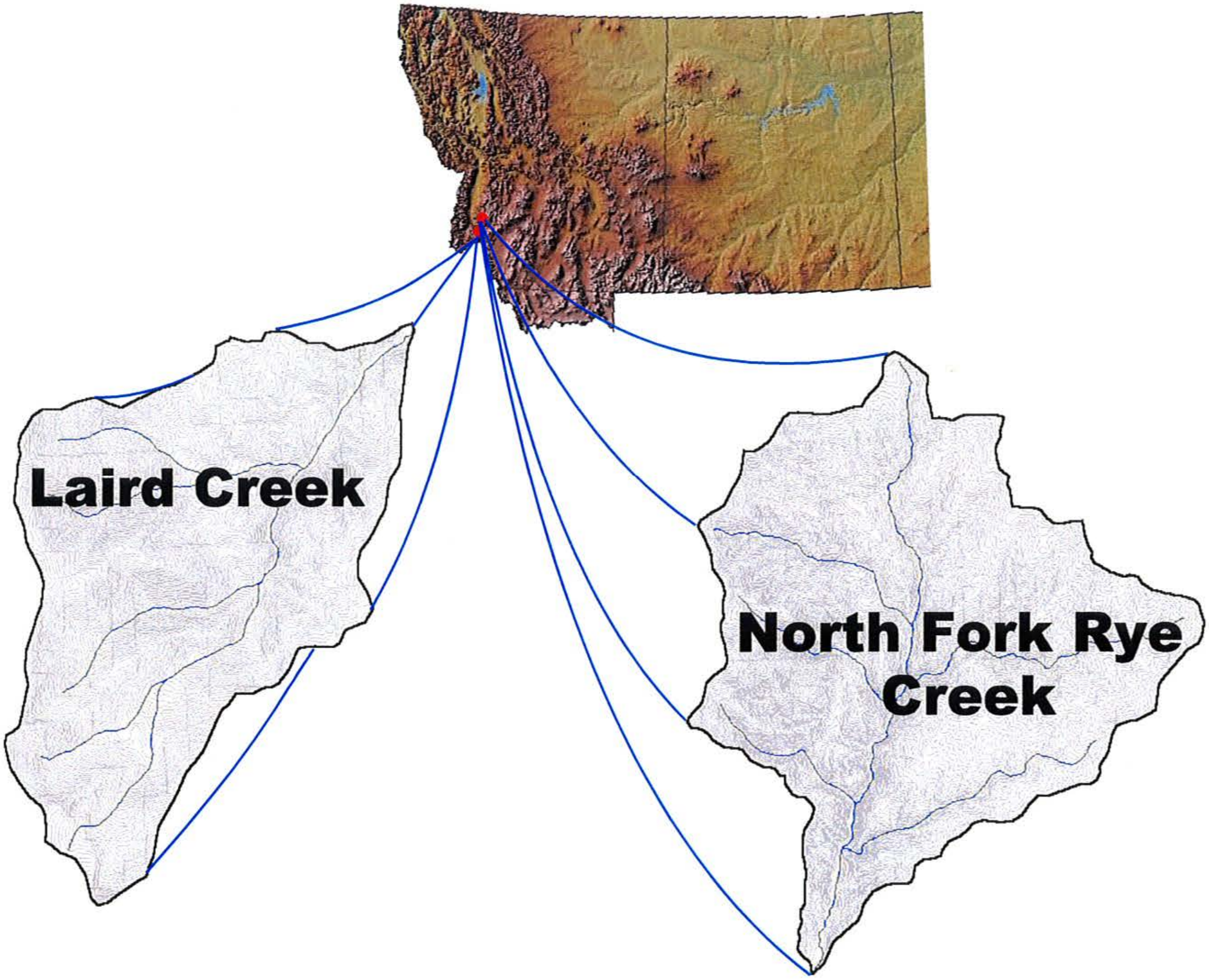
APPENDIX

RAINFALL EVENTS AND THEIR EFFECT ON SEVERELY BURNED AREAS OF WESTERN MONTANA FOLLOWING THE FOREST FIRES OF 2000



CONTENTS

RAINFALL EVENTS AND THEIR EFFECT ON SEVERELY BURNED AREAS OF WESTERN MONTANA FOLLOWING THE FOREST FIRES OF 2000

By Ray Nickless, Eric Boldt and Craig Neesvig

ABSTRACT

Convective rainfall events in western Montana that occurred on high intensity forest fire burn areas following the forest fires of 2000, resulted in flash flooding and debris flows. Typical summer thunderstorms produced excessive runoff while longer duration rainfall events produced no flooding. When threshold rainfall rates were met during the thunderstorm season of 2001, severely burned watersheds produced flooding while adjacent non-burned watersheds produced no flooding. Soils in high burn severity areas could not absorb the short burst of heavy rain that exceeded the threshold, however, soils were able to absorb long duration rainfall that exceeded more than one inch. Antecedent conditions from previous rain events appeared to have no effect on producing excessive runoff on future non-convective events. A frequency analysis of ½ hour precipitation events revealed recurrence intervals of 5-10 years and 10-25 years. Indirect discharge measurements of post-storm events made by the United States Geological Survey and subsequent frequency analysis performed on the discharge data indicated 100 to 500 year recurrence intervals for the flood flows. Comparing the frequency of the rainfall events to the flood flow data clearly showed that the forest fires of 2000 had altered runoff potential from the watersheds. Debris and hyperconcentrated flows in normally ephemeral draws demonstrated the energy and erosive potential of runoff produced from thunderstorms that hit high severity burn areas.

INTRODUCTION

Forest fires that occurred in the summer of 2000 burned large tracts of land in western Montana. Approximately 356,000 acres of forested land were burned in the mountains surrounding the southern end of the Bitterroot Valley with many rural residents losing homes to the flames (Figure 1). Once the fires had dissipated the first week of September, the focus turned to possible flood threats in the rural residential interface. Many homes that survived the fires and new homes being built next to the burned areas were at risk of being flooded. Small watersheds in the Bitterroot National Forest had soils that were altered by high intensity forest fire and this left the landscape susceptible to increased runoff. Laird Creek and North Fork Rye Creek were two watersheds were the residential interface was at a high risk of flooding. Laird Creek is a small tributary of the East Fork of the Bitterroot River near the town of Sula, Montana and North Fork Rye Creek feeds Rye Creek which enters the Bitterroot River between the towns of Conner and Darby, Montana. United States Forest Service (USFS) mapping of the watersheds indicated high intensity burn severity across some portion of these drainages. This type of burn left the hillsides void of vegetation and duff layers which intercept and absorb precipitation. A series of precipitation events occurred across the watersheds over the next water year (October 2000 - September 2001). Long duration rainfall events caused little runoff from the watersheds while

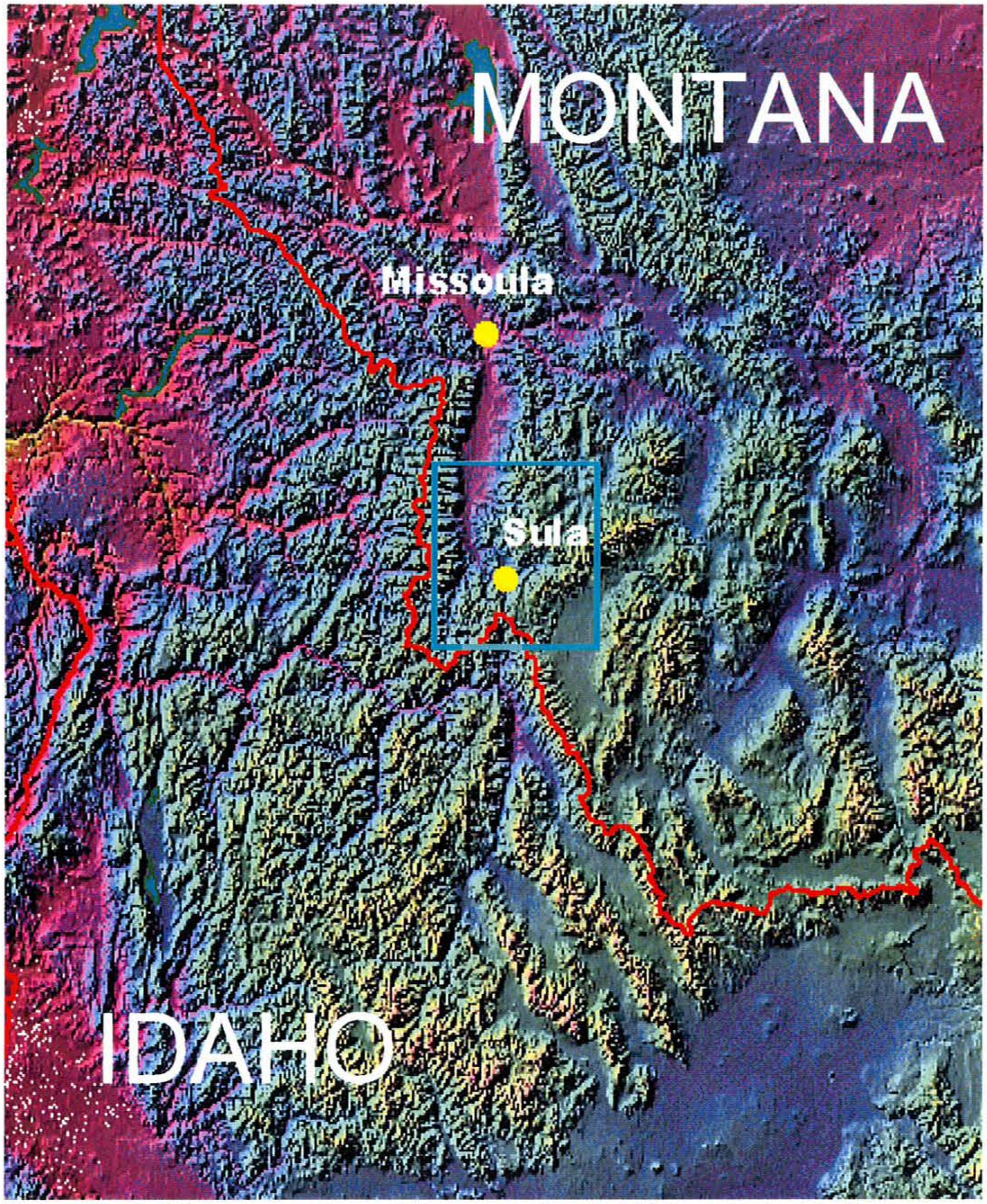


Figure 1. Relief map of southwest Montana and central Idaho. Blue box indicates general region where major fires occurred in the summer of 2000.

high intensity short duration storms caused flash flooding. The comparison of precipitation events and their effect on the watersheds is the focus of this paper.

WATERSHED CHARACTERISTICS

Laird Creek is a perennial stream which drains from the southern end of the Bitterroot Mountains on the Bitterroot National Forest. The watershed has a drainage area of 9.3 mi^2 and flows into the East Fork of the Bitterroot River approximately 4.85 mi downstream of Sula, Montana. The forest is mainly comprised of Douglas-fir and ponderosa pine. Stands of Douglas-fir are noticed on all slopes and aspects from the lowest elevations to the highest peaks while ponderosa pine are primarily on south facing aspects and exist in the elevation range of 4300 ft to 6800 ft. The mountains were formed by the intrusion of the Idaho batholith and the underlying geology is predominantly tertiary granite. Some hyperabyssal intrusive flows can be noticed at higher elevations and quaternary alluvium deposits closer to the basin outlet. The underlying granite has been weathered and the predominant soil type is granitic. Topography in the watershed ranges from 4245 ft at the basin outlet to a high of 8409 ft at Medicine point. Hillside slopes have extremes of 36% in the heavily timbered middle elevations and gentler 5% slopes in the alluvial deposits at lower elevations.

North Fork Rye Creek is also a perennial stream that flows into Rye Creek and eventually reaches the Bitterroot River near Highway 93 approximately 5 miles upstream of Darby, Montana. The watershed is predominantly forested and has a size of 18.4 mi^2. The majority of the trees in the watershed are Douglas-fir that comprise 75% of the forest with lodgepole pine, ponderosa pine and sub-alpine fir representing the rest. Topography was formed by the Idaho batholith intrusion and underlying geology consists of cretaceous granitic diorite and Precambrian metamorphic gneiss in the higher ridge line elevations. Elevations range from 4232 ft at the basin outlet to 7284 ft at the highest point which is Deer Mountain. Most slopes have a gradient of 15-18% with some 37% grades which leave some sections of the watershed susceptible to flashier runoff response.

DATA SOURCES

In April 2001 the United States Geological Survey (USGS), USFS and National Weather Service installed precipitation gages in various watersheds of the Bitterroot National Forest to record rainfall data (Figure 2). In order to determine stream discharge and height in the Laird Creek watershed, a river gage with recording devices was established at the basin outlet (Figure 3). Data was recorded every 5 minutes and stored on a computer chip for later data retrieval. The National Weather Service (NWS) also attached a Handar 750A data collection platform to the co-located river and tipping bucket precipitation gage. Precipitation and stream gage height data were collected in real-time via a phone line that was interrogated every ½ hour from a personal computer at the NWS office in Missoula, Montana. A crest stage gage was installed in the North

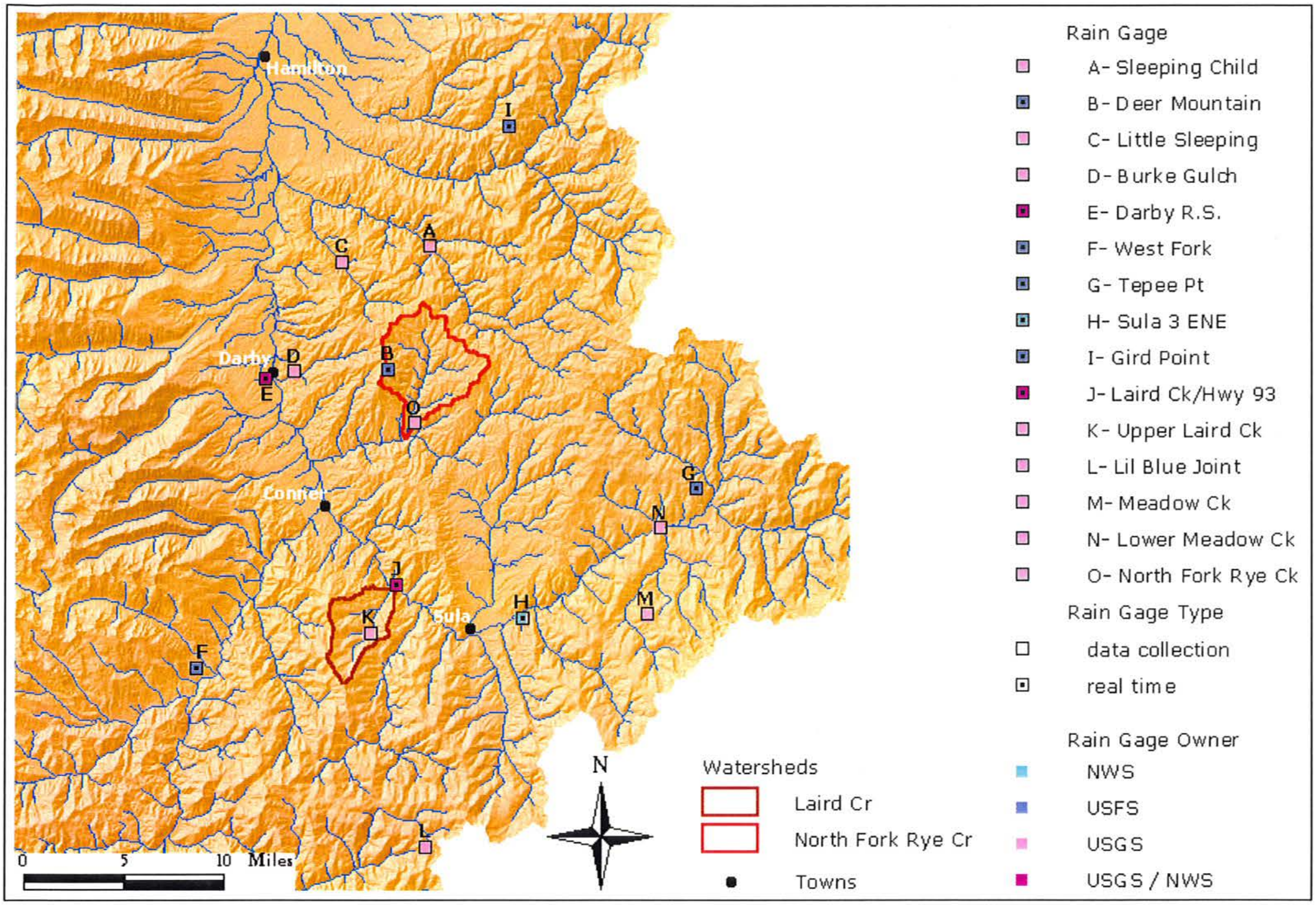


Figure 2. Raingage network in the southern end of the Bitterroot Valley.

Figure 3. USGS river gage and tipping bucket precipitation gage with recording devices at mouth of Laird Creek.

Fork Rye Creek watershed to capture peak flow heights and a tipping bucket precipitation gage was also installed in the middle of the basin. The USFS installed a Remote Automated Weather Site (RAWS) that collects meteorological data including rainfall data every hour, this data was transmitted real time via Geostationary Orbiting Environmental Satellite (GOES) telemetry to the NWS office in Missoula, Montana. Data from these locations was used to evaluate the frequency of precipitation events and their affect on runoff from the burn areas. NWS Doppler Radar estimates were also compared to data from the precipitation gages.

FOREST FIRE BURN SEVERITY

The burn severity areas of the Bitterroot National Forest were mapped by USFS hydrologists and soil scientists from helicopter reconnaissance and verified by ground visits (Figure 4). Fire severity is a qualitative measure of fire effects on a component of the ecosystem (Robichaud, 1997) and the burn severity mapping done in the Bitterroots was based on guidelines developed by the USFS. These guidelines are defined in the USFS Handbook Series 2509.13 under the section of burned-area emergency rehabilitation.

High Burn Severity Definition

A high intensity burn area is determined when 40 percent or more of the area exhibits the following characteristics:

1. Ashes are white or reddish color, indicating that much of the carbon was oxidized by the fire, especially if they are over 2 inches in depth. This consistently indicates zones of intensive burn with long residence time.
2. When fuels greater than 0.75 inches in diameter and more than 80 percent of the plant canopy have been consumed.
3. Litter is totally consumed with only a few ashes remaining on the soil surface.
4. Plant root crowns of sprouting brush and grasses are consumed or heavily damaged by the fire.
5. The soil surface is crusted or baked.

Medium Burn Severity Definition

A medium intensity burn area is determined when less than 40 percent of the area exhibits high burn severity and the following characteristics:

1. Sparse ashes that are darker in color.
2. When fuels 0.5 inches in diameter and 60 percent of the plant canopy have been consumed.
3. Litter is charred but not ashed.

Low Burn Severity Definition

A low intensity burn area is determined when moderate or low-intensity characteristics are met on the entire area:

1. Sparse ashes that are darker in color.
2. When fuels up to 0.25 inches in diameter and less than 40 percent of the brush canopy have been consumed.

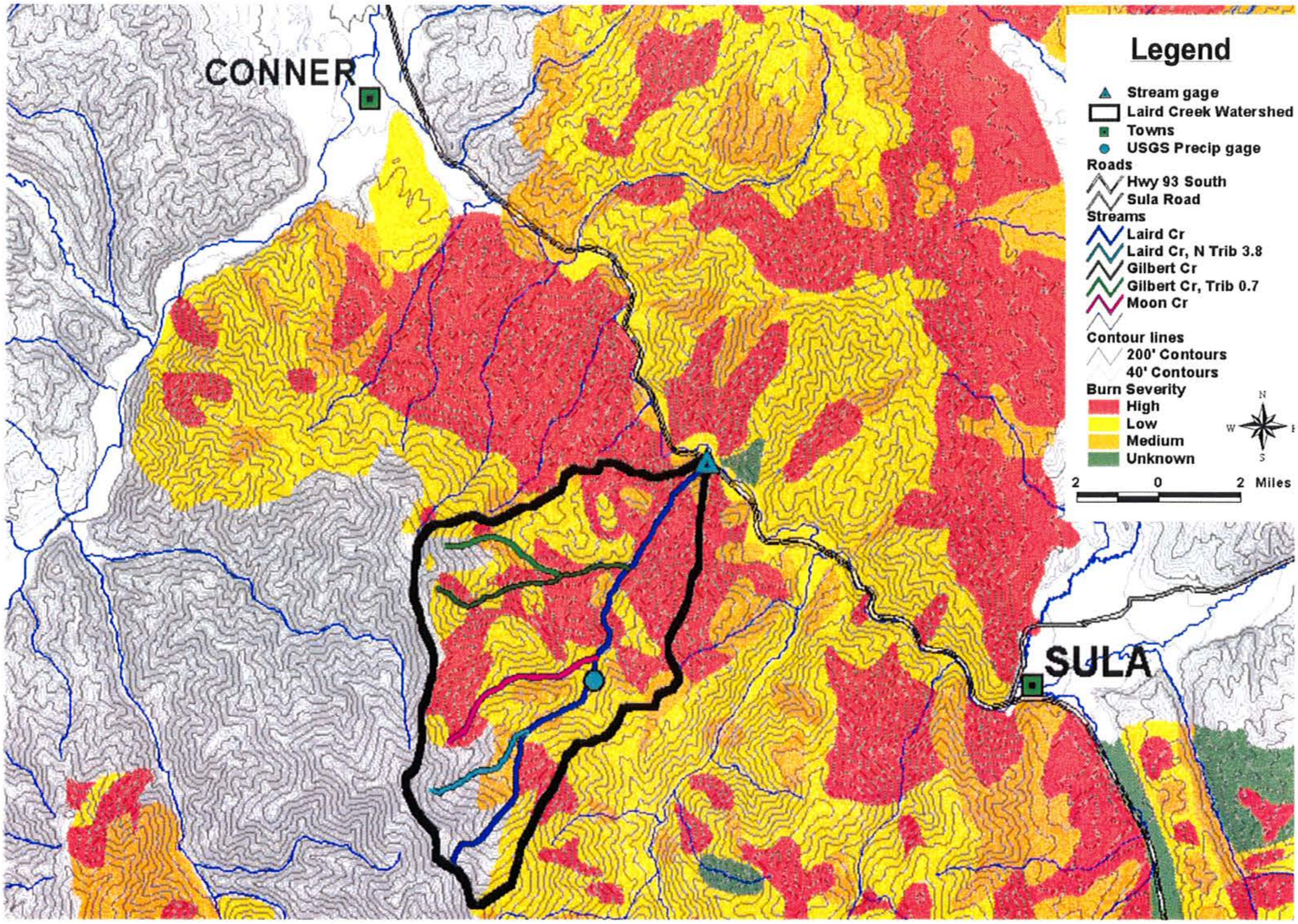


Figure 4. Fire Burn Severity for the Laird Creek Watershed and surrounding area.

3. Litter has only been singed.

HIGH INTENSITY BURN EFFECT ON VEGETATION AND SOILS

An analysis of the predominant vegetation and soils in the high burn severity areas of the Laird and North Fork Rye Creek watersheds was completed in order to determine how the loss or change of each component would affect watershed response. Analysis of Geographic Information System (GIS) spatial layers obtained from the USFS indicated the following:

(1) 70%-75% of the high burn severity occurred on forest associated with Douglas-fir habitat, 17% in ponderosa pine stands and the remaining 10% occurred on small tracts of lodgepole pine and sub-alpine fir.
(2) The predominant soil classification throughout the watersheds in the high burn severity areas consists of sandy to loamy, mixed cryochrepts and loamy-skeletol ustochrepts. Both of which, are highly erosive in steep slopes, and contain relatively shallow soil horizons.

No correlation could be determined between different tree species and their affect on runoff, however, the loss of tree canopy and duff layers associated with the species had an affect on runoff and erosion. The total amount of interception by trees, shrubs, grasses and duff layer can add up to a significant amount as studied by Helvey and Zinke. The amount of water required to wet the vegetation (average rainfall storage values) ranges from 0.013 inches to 0.09 inches for coniferous and hardwood forests of the United States, according to a review by Helvey (1971) (Tiedemann & others). A summary by Zinke (1967) showed that interception by shrubs and grasses averages .05 inches and that storage values on the forest floor average about 0.16 inches (Tiedemann & others).

No field tests of soils were conducted by the authors to determine if hydrophobicity existed, however, the relationship between intense heating of soil and associated hydrophobicity is well documented by DeBano (1981). Any mineral soil containing more than a couple of percent of organic matter is likely to become water repellent to some degree when heated (DeBano 1981). Studies by Megahan and Militor 1975, reported sheet erosion and rilling on granitic soils in Idaho were both greatly accelerated following a wildfire on a clearcut area of mixed Douglas-fir and ponderosa pine (Tiedeman & others). It stands to reason that some hydrophobicity should exist in the high burn severity areas of the Bitterroot Watersheds considering the effects that intense heating has on soils.

RAINFALL THRESHOLDS

Rainfall threshold rates for high burn severity areas of the Bitterroot National Forest had been established by the NWS in Missoula, Montana prior to the summer of 2001. The rainfall threshold rate being used to predict flash flooding was 0.25 inches in less than an hour. The threshold value was established by investigations of long duration and short duration rainfall events that occurred in the fall months of September and October of 2000. Raingage data from USFS RAWS and NWS cooperative observers along with NWS Doppler Radar data were analyzed. The most conclusive data came from the Pardee Creek RAWS located in the Lolo National Forest near the town of Superior, Montana. In September 2000, a rainfall event occurred over a forest fire burn area known as the Thompson Flat Complex near Superior. In that event, 24 hour storm total rainfall of 0.60 inches was measured with 0.20 inches occurring in less than an hour. A subsequent investigation of the area by the authors revealed flash flooding and debris flow from a high burn severity section of the fire complex.

WEATHER BACKGROUND

The southern Bitterroot Valley in southwest Montana averages between 30 and 50 thunderstorm days a year (Figure 5) and is the most active convective area in the Weather Forecast Office (WFO) Missoula county warning area (CWA). According to *Storm Data*, Ravalli County in southwest Montana averages one severe thunderstorm event each year with data heavily weighted by weather spotter reports in the Bitterroot Valley. In 2001, the WFO Missoula CWA had a total of 21 severe events, one of which occurred in Ravalli County. In addition, no severe thunderstorms were recorded during the three flash flood events mentioned in this paper.

There is a higher frequency of thunderstorms in southwest Montana compared to the rest of western Montana mainly because of the steep mountainous terrain, ranging from roughly 7000 ft to over 10000 ft peaks, high elevated valleys, and the occasional presence of monsoon moisture during the summer months. A strong four-corners high pressure system in the upper atmosphere and low pressure trough along the west coast, results in south to southwesterly winds aloft over the Pacific Northwest and northern Rockies. This wind pattern moves monsoon moisture, originating from the desert Southwest of the United States and Old Mexico, northward across the Great Basin and into southwest Montana.

Strong afternoon surface heating during a summer day and a layer of mid-level moisture can lead to development of convection in updrafts near mountain ridges. A shortwave trough and/or a jet streak in the upper atmosphere can help organize thunderstorms into longer-lived single or multiple cells that are more likely to move out across valley areas. Usually, thunderstorms in western Montana are pulse-type events lasting less than an hour.

DOPPLER RADAR CONSIDERATIONS

The WFO Missoula Doppler Radar (KMSX) is located on Point Six Mountain approximately 8 nm north of the WFO Missoula office, at an elevation of 8039 ft MSL. The vast majority of the severely burned areas of 2000 are located roughly 70 nm to the south of the radar near the town of Sula, at 5160 ft MSL. The lowest elevation scan (0.5° tilt) of the KMSX radar beam at this

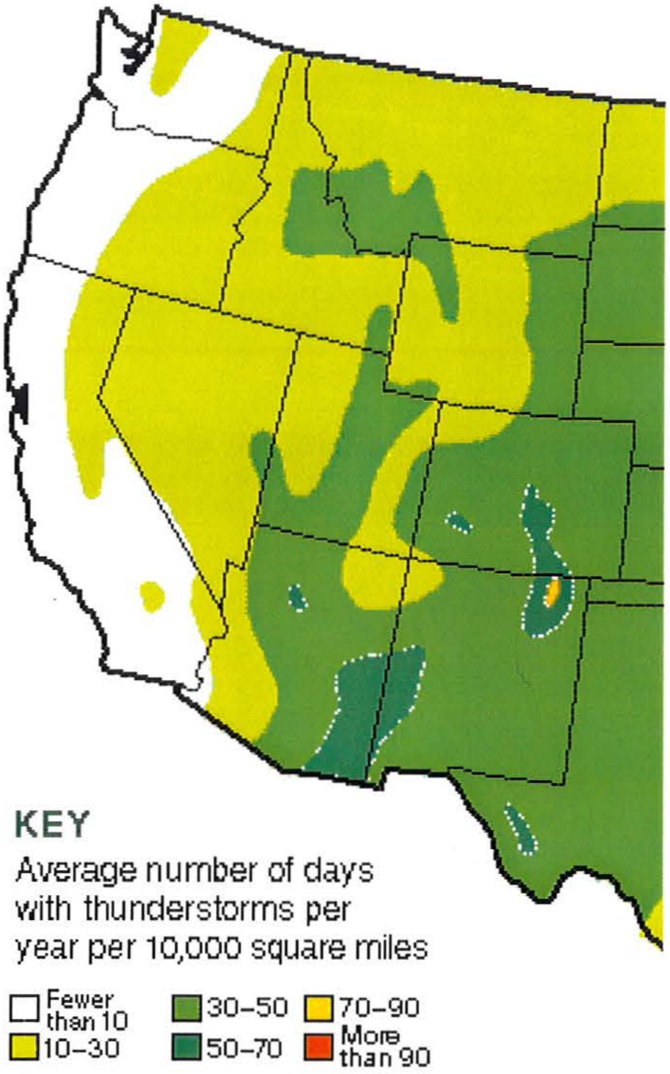


Figure 5. Average thunderstorm days.
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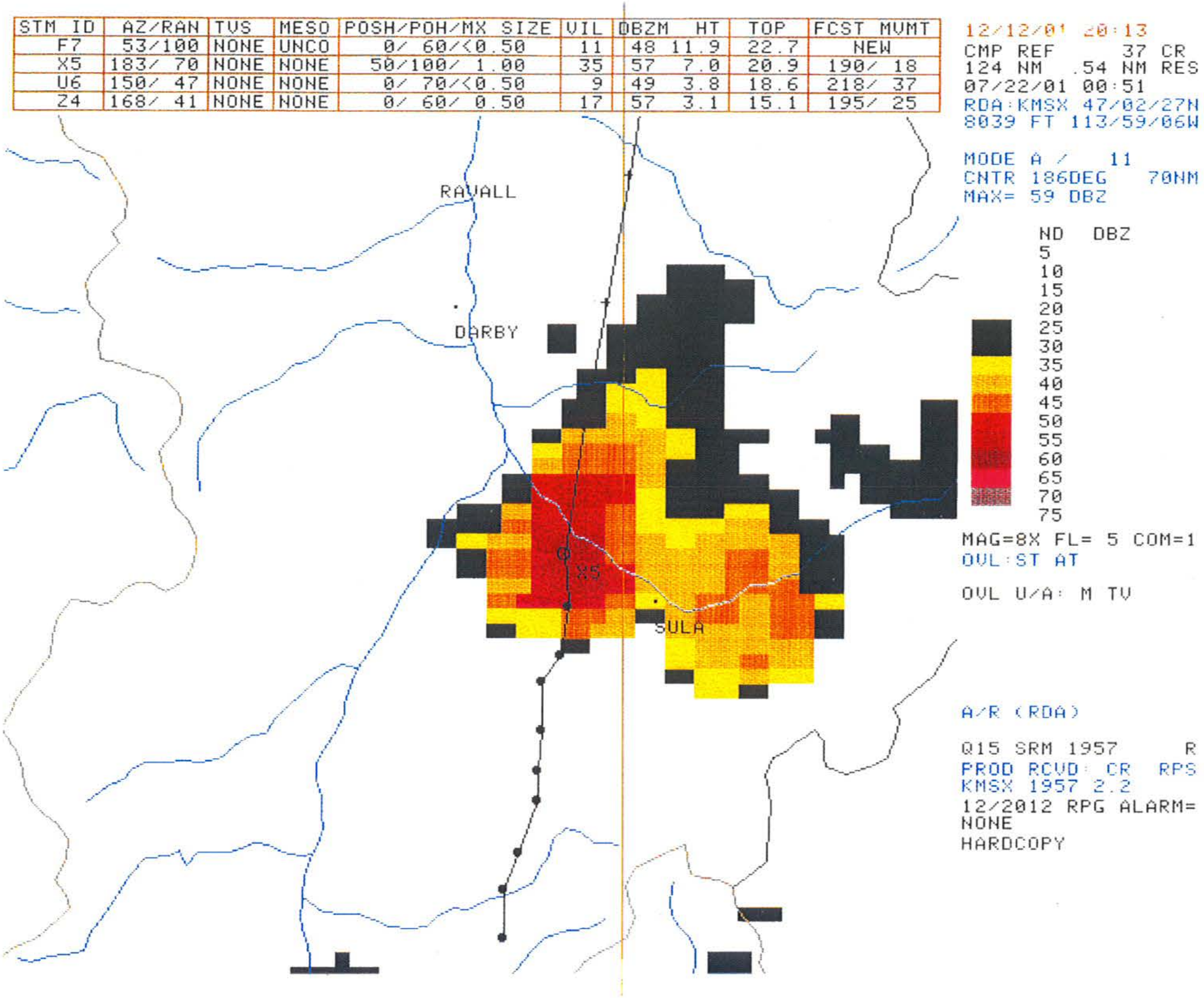
distance is at an elevation of 15,700 ft MSL.

The elevated radar site of KMSX presents numerous problems with data quality and availability at farther distances from the radar. In all flash flood events that occurred in July 2001, the freezing level was between 11,000 ft and 14,000 ft MSL. The freezing level was below the lowest elevation scan of the radar beam 15,700 ft at this distance. Therefore, the Doppler sampled data is derived mainly of graupel and supercooled water droplets caught in thunderstorm updrafts. In each thunderstorm cell near Sula, the radar detected the maximum reflectivity at the level of the lowest elevation scan 15,700 ft (Figure 6). It was therefore unknown if stronger reflectivity returns occurred or extended well below the radar beam since the storm centroid elevation was unavailable. If we look at an earlier radar scan shown at a larger viewing angle (Figure 7), cell Z4 is stronger than cell X5 and positioned closer to the radar. However, the maximum reflectivity of cell Z4 (64 dbZ) occurred at the lowest elevation scan and therefore could be more intense below the radar beam as well. The inability of KMSX radar to detect significant reflectivities at lower elevations likely creates a trickle-down effect on the Doppler precipitation processing algorithms for generation of the one-hour precipitation estimate (OHP). Further study, beyond the scope of this research paper, could shed light on the significance of the OHP at elevated radar sites in the western United States.

The single-cell thunderstorms that moved over the severely burned watersheds from 15 July 2001 through 21 July 2001 were high intensity short duration precipitation (Egger and Vasiloff 1998) events, generally lasting no more than 30 minutes. Doppler OHP estimates are based on one-hour increments. This time lag associated with the OHP means the precipitation processing algorithm is continuously "catching-up" with actual storm activity by adding previous radar scans and time-averaging to formulate the OHP product. Given the quick runoff reaction of a burned forest in steep terrain, the OHP was not helpful in real-time since the flash flooding was already occurring by the time the radar indicated the heaviest rainfall. However, the OHP was useful in evaluation of upstream rainfall estimates prior to reaching the burned area and provided a storm track history.

The OHP gave varying results depending on the type of storm event compared to the recorded amounts in the rain gauge network (ground truth) near the burned areas. Two flash flood events, 15 July 2001 and 21 July 2001, were noted for their significant hail content with storm spotter reports of hail accumulations of one to two inches in depth. Radar reflectivity of thunderstorm cells ranged from 60-65 dbZ along with Vertically Integrated Liquid (VIL) values of 30-40 kg m^{-2} with these events. Some rainfall overestimation seemed likely but comparison between radar estimates and rain gauges showed fairly similar precipitation amounts. The flash flood event of 20 July 2001 did not include significant hail due to lower-topped thunderstorm cells, with peak reflectivities of 50-55 dbZ and VIL less than 20 kg m^{-2}. The OHP estimates were lower than the other events, as expected, however rain gauge amounts lead to the conclusion the OHP was underdone in this case. Rain gauges detected 0.4 inch amounts in the Laird Creek basin, which occurred in about a 30 minute time frame. The OHP showed an amount of 0.4 inches, but should have been closer to 0.8 inches per hour.



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X5	183/ 70	NONE	NONE	50/100/ 1.00	35	57 7.0	20.9	190/ 18
U6	150/ 47	NONE	NONE	0/ 70/<0.50	9	49 3.8	18.6	218/ 37
Z4	168/ 41	NONE	NONE	0/ 60/ 0.50	17	57 3.1	15.1	195/ 25

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OVL:ST AT

OVL U/A: M TV

A/R (RDA)

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PROD RCVD: CR  RPS
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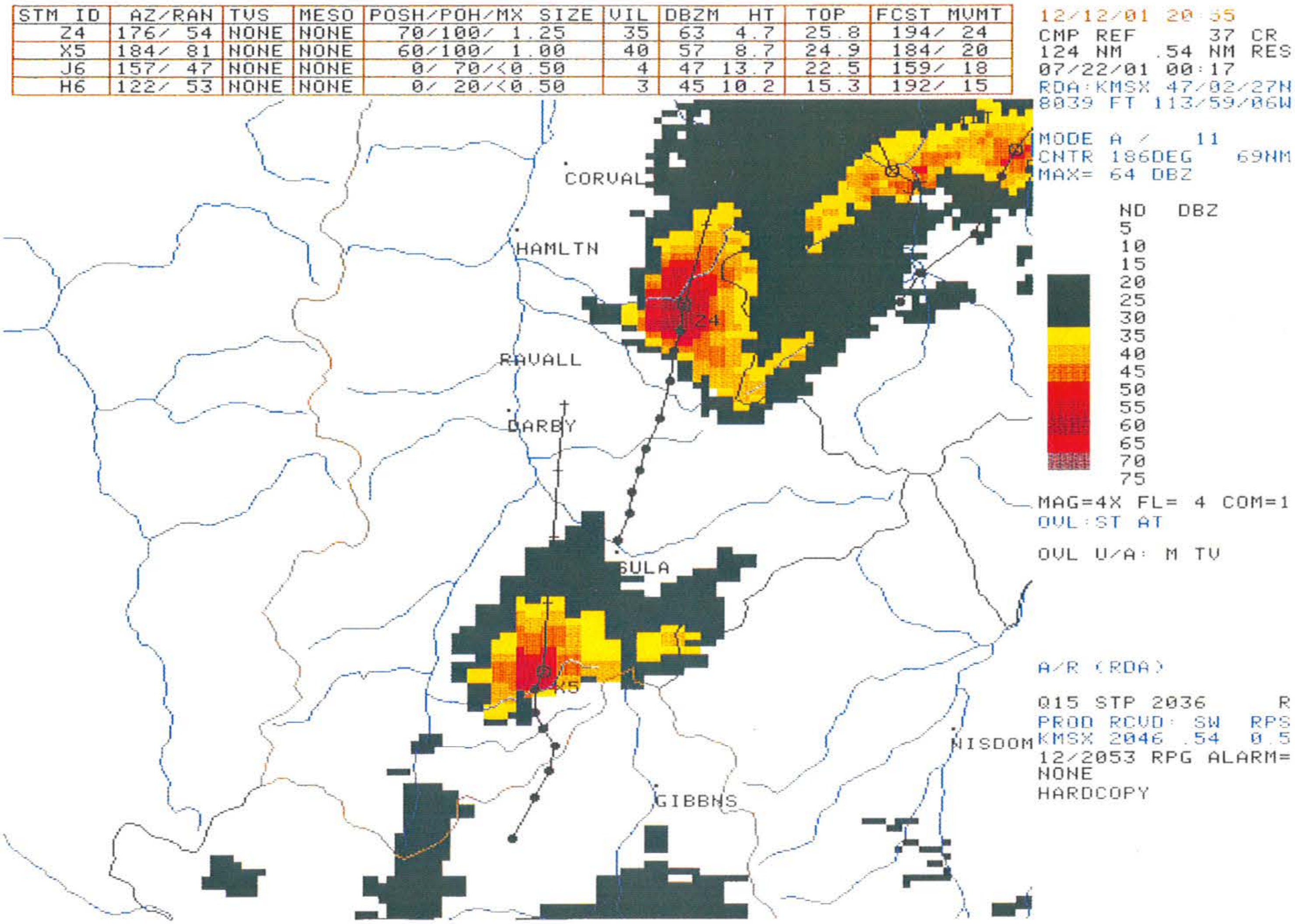
Figure 6. 0051 UTC 22Jul2001 KMSX composite reflectivity shows cell X5 from Fig. 7 directly over Laird Creek drainage.



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X5	184/ 81	NONE	NONE	60/100/ 1.00	40	57 8.7	24.9	184/ 20
J6	157/ 47	NONE	NONE	0/ 70/<0.50	4	47 13.7	22.5	159/ 18
H6	122/ 53	NONE	NONE	0/ 20/<0.50	3	45 10.2	15.3	192/ 15

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OVL V/A: M TV

A/R (RDA)

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HARDCOPY
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Figure 7. 0017 UTC 22Jul2001 KMSX composite reflectivity shows cell Z4 that moved over burn areas in the southern Bitterroot Mountains, originating near Sula, Montana. Cell X5 is approaching the Laird Creek drainage.

Radar OHP estimates give limited assistance during a flash flood event on severely burned areas located in steep terrain. Establishing a history of rainfall intensity and storm motion from prior storm cells are benefits, but lag time is too great to give real-time assistance of precipitation accumulation during a flash flood event. An analysis of precipitation data in smaller time increments for small watersheds, like available in AWIPS software upgrades containing the Area Mean Basin Estimated Rainfall (AMBER) system, would benefit forecasters by providing estimated precipitation data close to real-time.

FLASH FLOOD OVERVIEW

Weather patterns during all flash flood events were reflections of typical synoptic conditions for the summer season in western Montana, with low pressure across the eastern Pacific Ocean and high pressure over the southern Rockies. Although southwest Montana averages many more thunderstorm days (Figure 5) when compared to the rest of the WFO Missoula CWA, there was nothing unusual about the 2001 convective season. The only outlying factor during each episode that was not "normal" was a relatively high total precipitable water (TPW) value. TPW (Huschke, Glossary of Meteorology) is the total atmosphere water vapor contained in a column of unit cross-section extending all the way from the earth's surface to the "top" of the atmosphere. There is a general correlation between precipitation amounts in given thunderstorms and the precipitable water vapor of the air masses involved in those storms. A normal TPW value in western Montana is approximately 0.50 inches during the summer months (data provided by NOAA-CIRES Climate Diagnostics Center), but can often by closer to 0.30 inches during a extended dry period of approximately a week or more. Summer weather patterns more typically bring dry mid-level Pacific air across southwest Montana, resulting in dry sub-cloud layers and inverted-v sounding signatures. TPW values greater than 0.50 inches during July 2001 indicated a potential to more easily saturate water vapor in the low levels of the atmosphere, resulting in minimal evaporation and good precipitation efficiency (Doswell et al, 1996) during convection.

Forecasters should be aware of favorable conditions for wet thunderstorm development over their CWA, similar to the events that occurred in southwest Montana during July 2001. A saturated air mass with above normal TPW values will result in better accuracy of the OHP estimates and less overestimation, which might occur as a result of dry air in the lower layers below convective cloud bases. Also, storm motion generally less than 20 mph was adequate to achieve heavy rainfall in these flash flood events.

The following is a review of the flash flood cases of 15 July, 20 July, and 21 July 2001, including the synoptic weather pattern for each event that lead to heavy rainfall and eventual flooding, satellite pictures near the time of flash flooding, select ETA model data, and evaluation of the KMSX Doppler Radar performance.

Flash Flood Event - 15 July 2001

On 15 July 2001, upper level low pressure resided over the southwest corner of British Columbia

(Figure 8), resulting in a southwesterly flow aloft over the WFO Missoula CWA, which is a favorable pattern for thunderstorm development. In the afternoon, a weak shortwave and a 80 kt jet speed maxima were across western Montana (Figure 9). The best region of upper level divergence was positioned over southwest Montana and the 12-hour ETA model sounding for Hamilton (HMM), Montana, valid 0000 UTC 16 July 2001 (Figure 10) indicated steep lapse rates and buoyancy available. TPW values were well above normal according to the ETA model with values from 0.6 to 0.8 inches.

As in most summer afternoons with favorable convective potential for western Montana, the location where thunderstorms will form is difficult to pinpoint at best. Given the high TPW in the region on 15 July 2001 (Figure 9) and storm motion less than 20 mph, heavy rainfall was possible in the CWA. By 2:00 pm MDT (2000 UTC) thunderstorms developed rapidly southwest of Sula and began to move over burned watersheds of southwest Montana. Flash flooding occurred between 2030 UTC and 2230 UTC as thunderstorms crossed over the North Fork Rye Creek watershed.

Doppler Radar detected maximum reflectivities of 60 dbZ during the flash flood event with VIL of 30-35 kg m^{-2}. Storm spotters reported small hail, generally less than 0.5 inches, associated with VIL of this value. A hand-drawn analysis of the radar's storm total estimate superimposed over terrain and southwest Montana river basins (Figure 11 and table 4 in the "Appendix") shows relatively accurate precipitation estimates during the event when compared to the rain gauge network or ground truth.

The subsequent runoff from the high burn severity areas created flash flooding which washed out many roads and flooded homes at the base of normally dry draws. Rainfall data from a USGS tipping bucket gage in the middle of the watershed indicated 0.56 inches in 30 minutes and a USFS RAWS at the top of the drainage reported 0.29 inches for a 1 hour time span. A frequency analysis of the precipitation data was performed by the USGS and a recurrence interval of 5-10 years was determined for the storm, however, an indirect discharge measurement and subsequent frequency analysis of the flood flow data produced a recurrence interval of 100 years. These analysis provide insight to the potential of extreme runoff from high severity burn areas when hit with typical summer thunderstorm rains.

Flash Flood Event - 20 July 2001

A similar convective weather pattern was in place on 20 July 2001. A cold-core upper low over western Oregon (Figure 12) was supplying strong divergence aloft over the Northern Rockies. Once again a weak shortwave aloft spun off the upper low (Figure 13) and 80 kt winds at 250 mb moved over the burned area helping to initiate afternoon convection. TPW values remained above normal during this event with values from 0.6 to 0.8 inches. The sounding for HMM indicated steep 700-500 mb lapse rates of 7.4 °C km^{-1} and weak speed shear aloft(Figure 14). Thunderstorms erupted by midday across Idaho and moved into southwest Montana around 1900 UTC, similar timing as in the 15 July 2001 case, with flash flooding occurring in the burned areas from 2000 UTC to 2200 UTC.

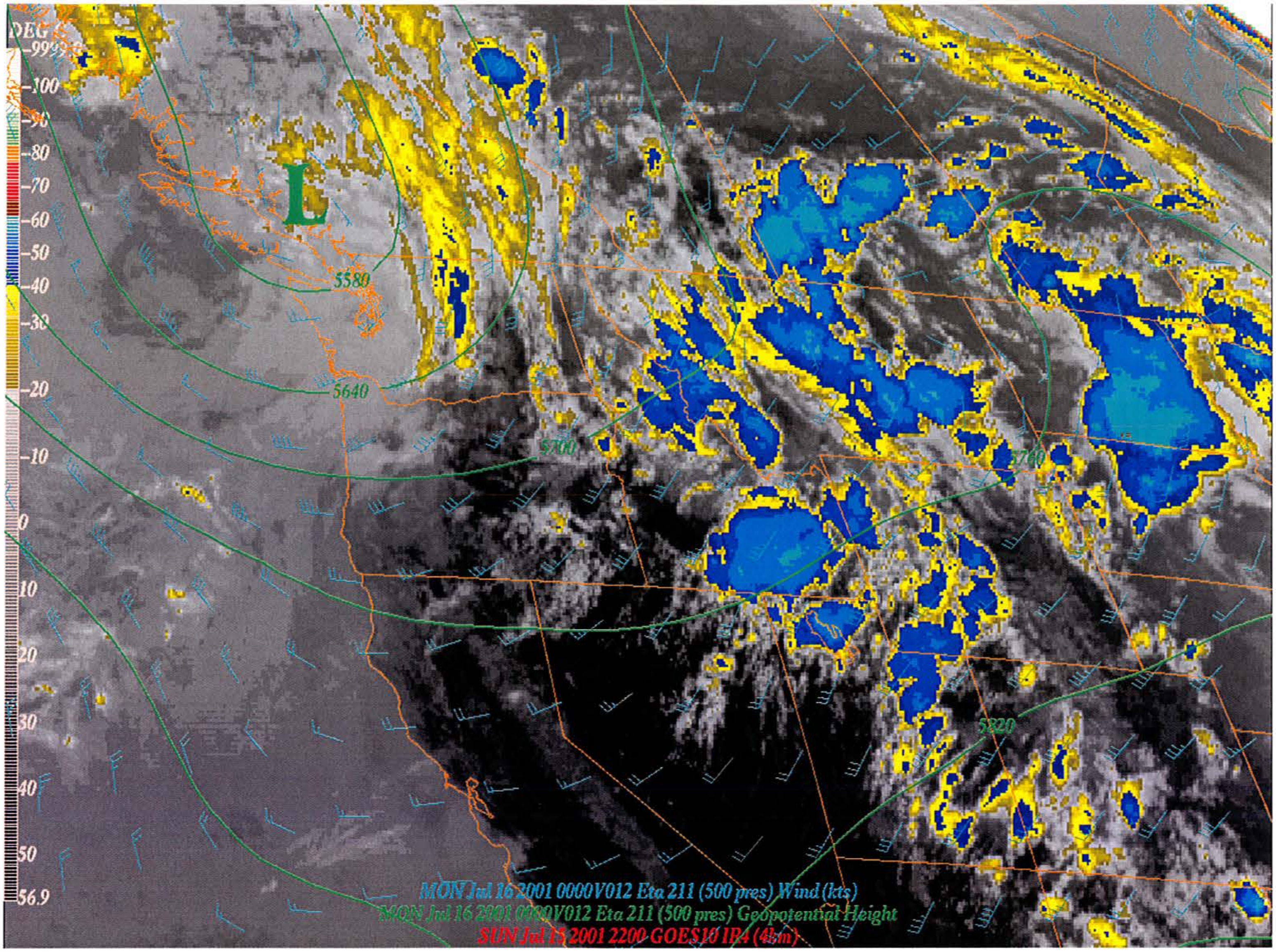


Figure 8. 2200 UTC 15Jul2001 infrared satellite, 500 mb heights (m) and wind barbs (kt).

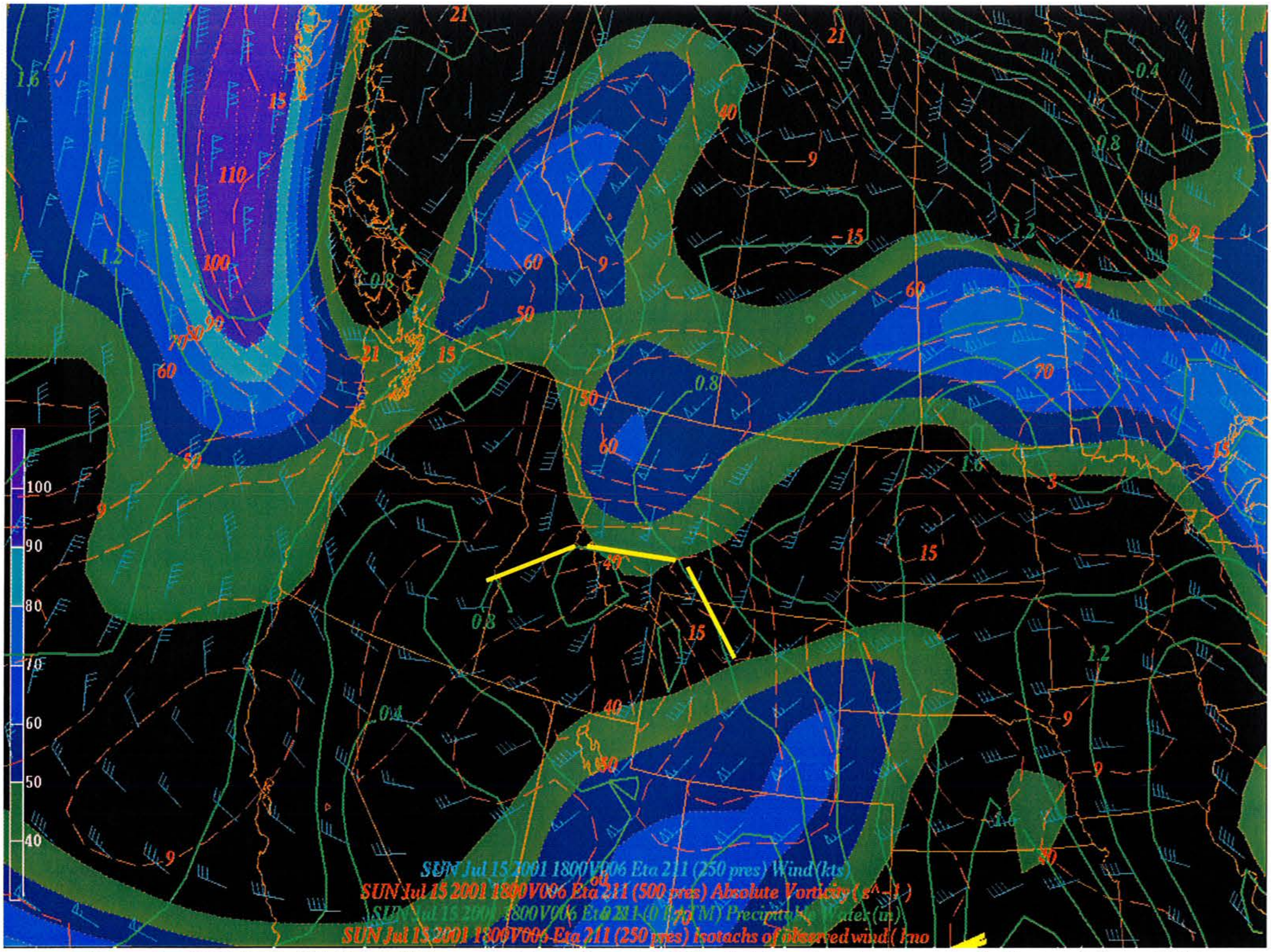
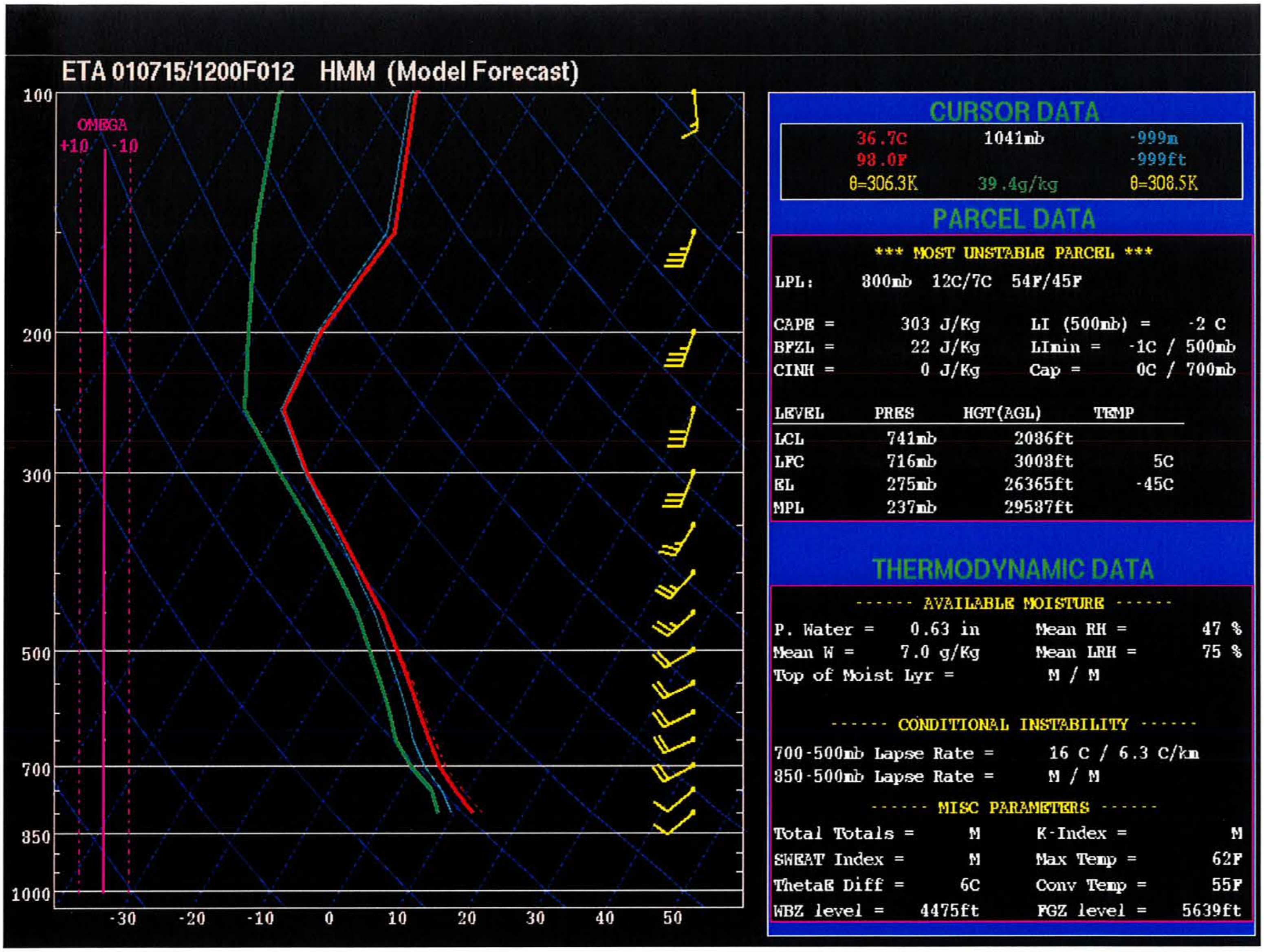


Figure 9. 1800 UTC 15Jul2001 ETA model 6-hour forecast, 250 mb jet contour image and wind barbs (kt), and total precipitable water (inch).



```
CURSOR DATA
     36.7C          1041mb          -999m
     98.0F                          -999ft
     θ=306.3K       39.4g/kg        θ=308.5K

PARCEL DATA
          *** MOST UNSTABLE PARCEL ***
LPL:      800mb  12C/7C  54F/45F

CAPE =        303 J/Kg     LI (500mb) =    -2 C
BFZL =         22 J/Kg     LImin =   -1C / 500mb
CINH =          0 J/Kg     Cap =      0C / 700mb

LEVEL      PRES      HGT(AGL)      TEMP
LCL        741mb      2086ft
LFC        716mb      3008ft         5C
EL         275mb     26365ft       -45C
MPL        237mb     29587ft

THERMODYNAMIC DATA
       ------ AVAILABLE MOISTURE ------
P. Water =    0.63 in      Mean RH =         47 %
Mean W =     7.0 g/Kg      Mean LRH =        75 %
Top of Moist Lyr =          M / M

     ------ CONDITIONAL INSTABILITY ------
700-500mb Lapse Rate =      16 C / 6.3 C/km
850-500mb Lapse Rate =      M / M
        ------ MISC PARAMETERS ------
Total Totals =      M      K-Index =          M
SWEAT Index =       M      Max Temp =       62F
ThetaE Diff =      6C      Conv Temp =      55F
WBZ level =    4475ft      FGZ level =   5639ft
```

Figure 10. 12-hour ETA model sounding for Hamilton (HMM), Montana, valid 0000 UTC 16 July 2001.

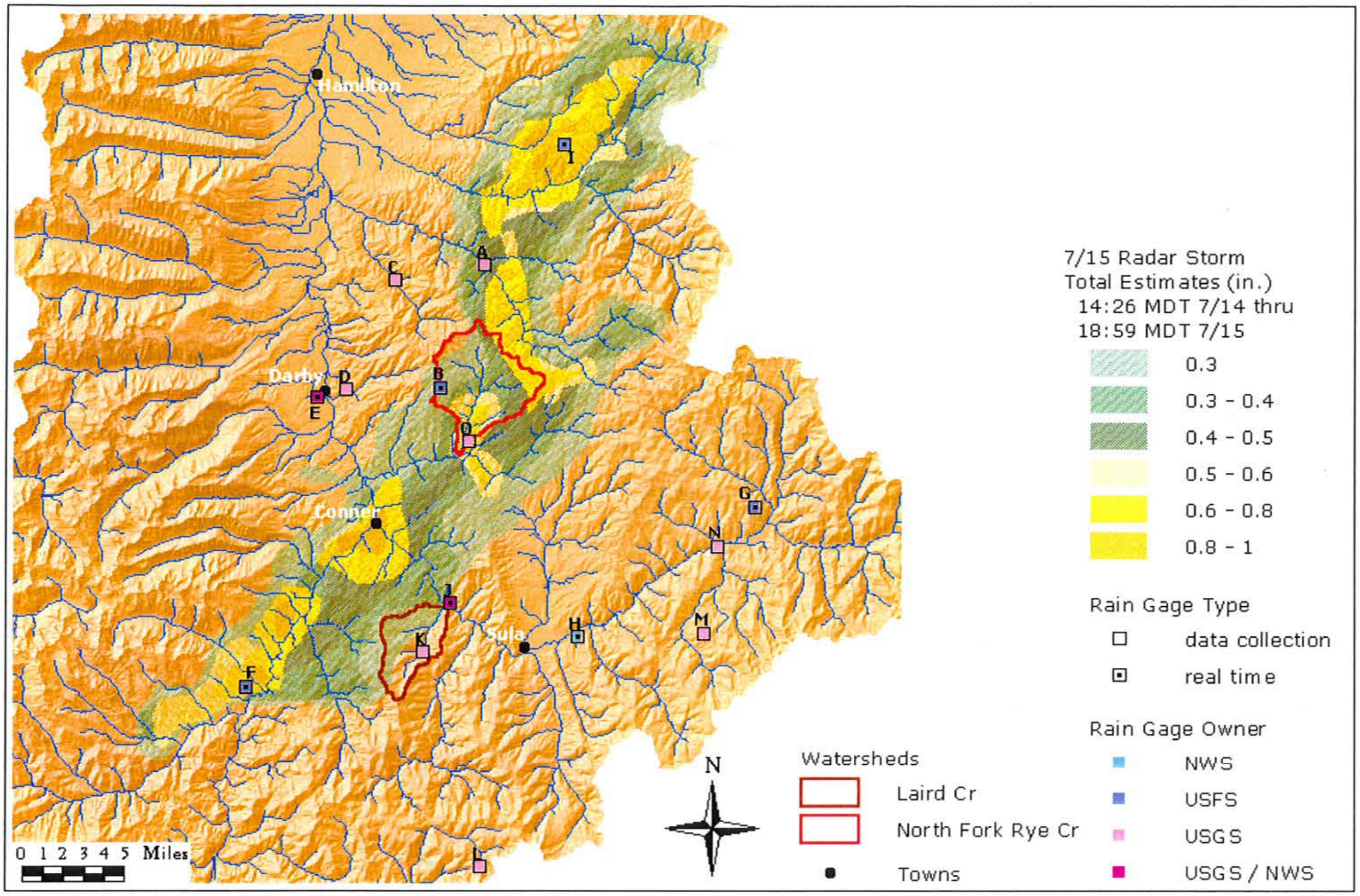


Figure 11. July 15th radar precipitation total compared to storm total raingage data in the southern Bitterroots.

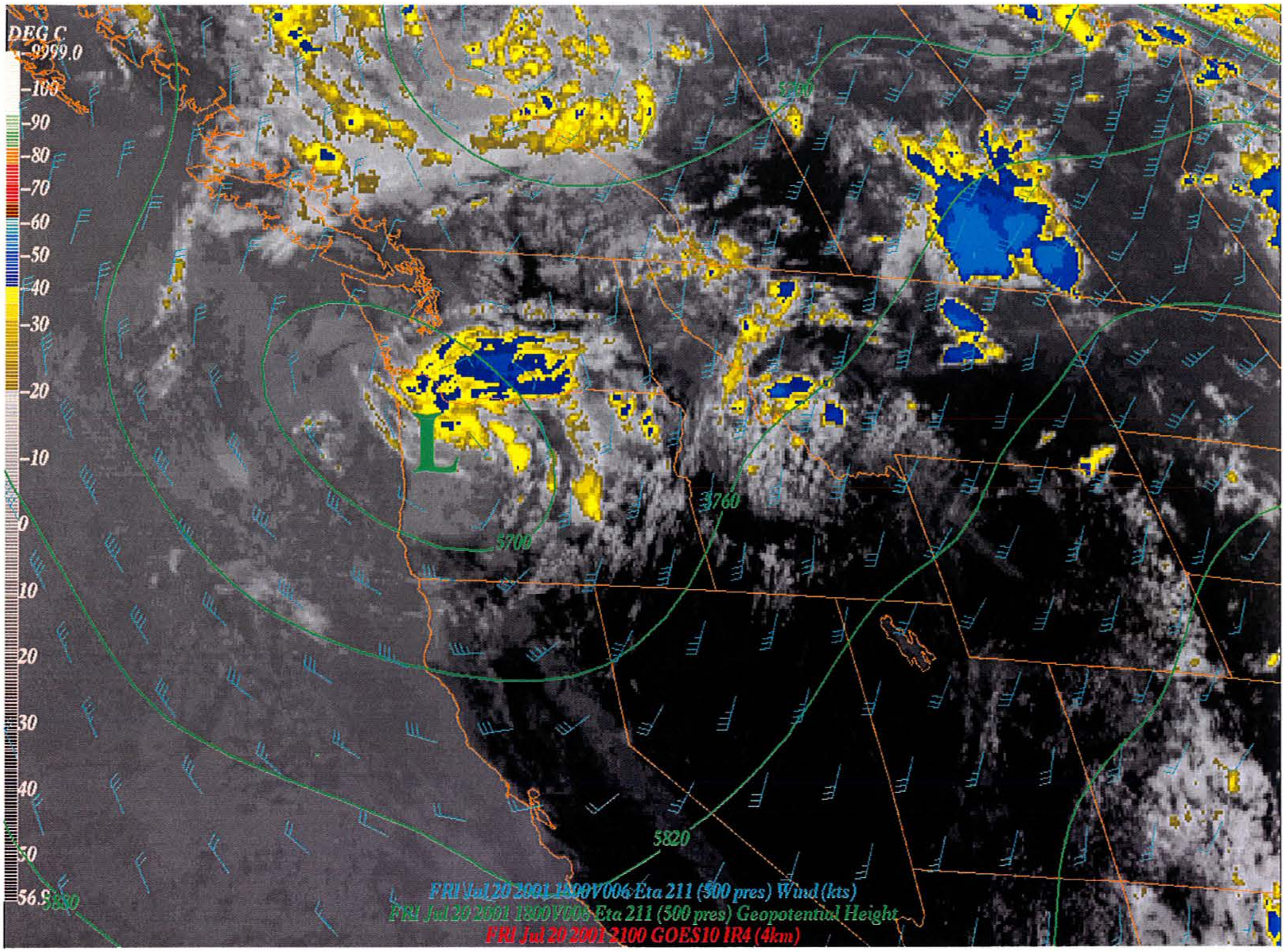


Figure 12. 2100 UTC 20Jul2001 infrared satellite, 500 mb heights (m) and wind barbs (kt).

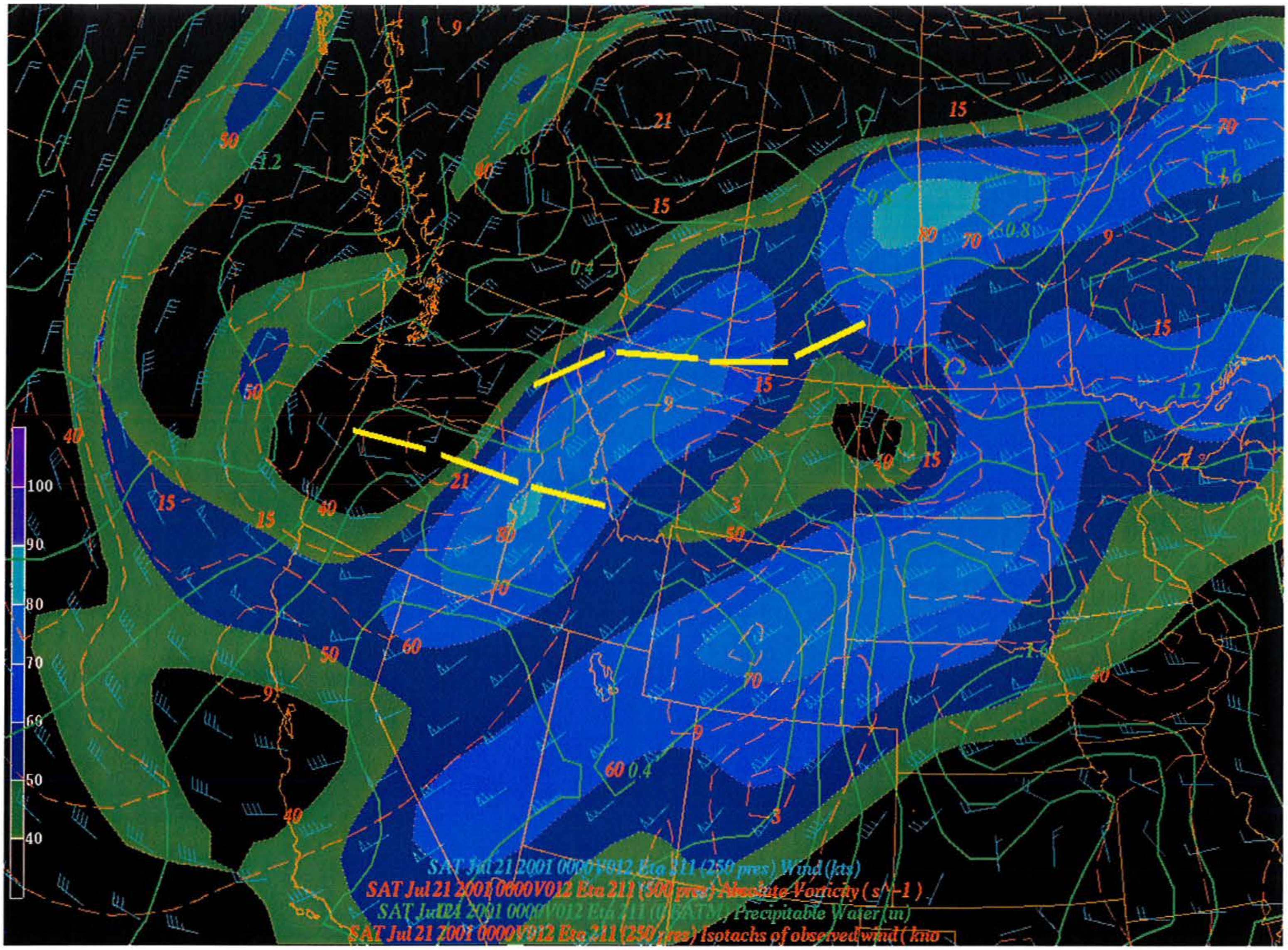
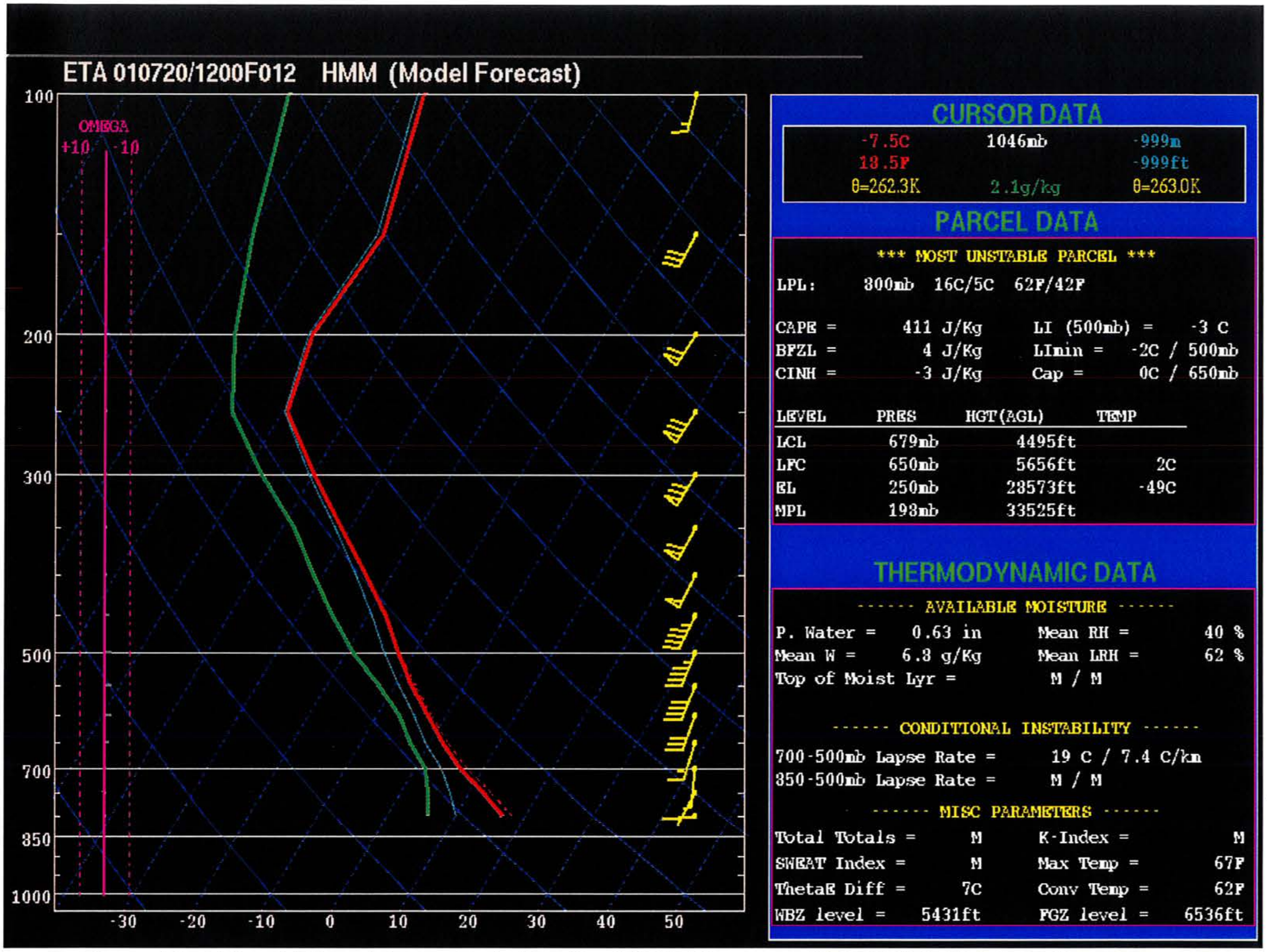


Figure 13. 1200 UTC 20Jul2001 ETA model 12-hour forecast, 250 mb jet contour image and wind barbs (kt), and total precipitable water (inch).



```
CURSOR DATA
  -7.5C          1046mb          -999m
  18.5F                          -999ft
  θ=262.3K       2.1g/kg         θ=263.0K

PARCEL DATA
      *** MOST UNSTABLE PARCEL ***
LPL:      800mb  16C/5C  62F/42F

CAPE =        411 J/Kg     LI (500mb) =    -3 C
BFZL =          4 J/Kg     LImin =   -2C / 500mb
CINH =         -3 J/Kg     Cap =      0C / 650mb

LEVEL       PRES      HGT(AGL)      TEMP
LCL         679mb      4495ft
LFC         650mb      5656ft         2C
EL          250mb     28573ft       -49C
MPL         198mb     33525ft

THERMODYNAMIC DATA
     ------ AVAILABLE MOISTURE ------
P. Water =   0.63 in      Mean RH =        40 %
Mean W =    6.8 g/Kg      Mean LRH =       62 %
Top of Moist Lyr =          M / M

     ------ CONDITIONAL INSTABILITY ------
700-500mb Lapse Rate =      19 C / 7.4 C/km
850-500mb Lapse Rate =      M / M

     ------ MISC PARAMETERS ------
Total Totals =        M     K-Index =          M
SWEAT Index =         M     Max Temp =       67F
ThetaE Diff =        7C     Conv Temp =      62F
WBZ level =    5431ft       FGZ level =   6536ft
```

Figure 14. 12-hour ETA model sounding for Hamilton (HMM), Montana, valid 0000 UTC 21 July 2001.

Doppler Radar detected maximum reflectivities of 51 dbZ during the event with VIL of 15-20 kg m $^{-2}$. Some hail was reported by spotters but thunderstorm cells were weaker than in the other flash flood events. The OHP estimates showed a maximum of 0.4 inches which was underdone when compared to the rain gauge network. Radar precipitation estimates should be about double those found in (Figure 15) to match ground truth(Table 5 in the "Appendix"*)* since the rainfall lasted about 30 minutes. Rainfall recorded at the USGS tipping bucket raingage at the mouth of Laird Creek reported 0.42 inches in a 30 minute time span (Figure 16). The resulting flood hydrograph from the USGS River gage at the same location reported a 6.5 ft rise in 30 minutes with a peak of 8.58 ft. The flood wave exceeded the capacity of the 48 inch culvert at Highway 93 and overtopped the road. Travel between Idaho and Montana was temporarily shutdown to remove debris from the highway. NWS and USGS frequency analysis on the storm revealed a recurrence interval of 5-10 years while the USGS frequency analysis of the resulting flood flow indicated a 500 year recurrence interval (Figure 16). The frequency analysis clearly indicates that the previous years fire had altered the runoff potential of the Laird Creek Watershed.

Flash Flood Event - 21 July 2001

Very little had changed in the synoptic pattern on 21 July 2001 from the previous day. A southwesterly jet remained over the region while the upper low had moved from western Oregon to central Washington. Weak shortwaves continued to rotate over southwest Montana with good upper divergence and steep lapse rates predicted by the 1200 UTC ETA model run. Residual low-level moisture from the previous day's thunderstorms contributed to a slower climb in afternoon temperatures over the area, therefore convection was not initiated until later in the day. Thunderstorms developed across Idaho before 5:00 pm MDT (2300 UTC) and moved into southwest Montana by 2330 UTC. Flash flooding occurred across southwest Montana between 2300 UTC 21 July 2001 and 0200 UTC 22 July 2001 as strong single-cell thunderstorms moved northward at 20 mph across numerous burned watersheds (Figures 6 and 7).

Doppler Radar detected stronger cells than on 20 July 2001 with maximum reflectivities of 60-65 dbZ and VIL of 30-35 kg m $^{-2}$. The OHP maximum (Figure 17 and table 5 in the "Appendix") exceeding 1.5 inches was deemed fairly accurate (30 minute storm rainfall total compared to the previous day's event) considering the high reflectivity values and numerous spotter reports of 0.5 inch hail covering the ground up to 2 inches in depth. Data collected from the rainfall and river gages showed a rain and flood event that was similar to the one that occurred on the 20th (Figure 18). The 30 minute storm total on the 21st produced 0.54 inches of rain which was 0.12 inches more than the July 20th event. The NWS and USGS rainfall frequency analysis showed a recurrence interval of 10-25 years for the July 21st storm. The resulting hydrograph had to be reconstructed using 30 minute data from the NWS telemetry device due to a failure in the USGS 5-minute data recorder (Figure 18). USGS indirect discharge measurements and flood frequency analysis indicated a flow of 230 cfs which was slightly greater than a 500 year recurrence interval.

Non-Flash Flood Event - 29-31 July 2001

A longer duration rain event hit the watershed approximately one week later on 29 July through

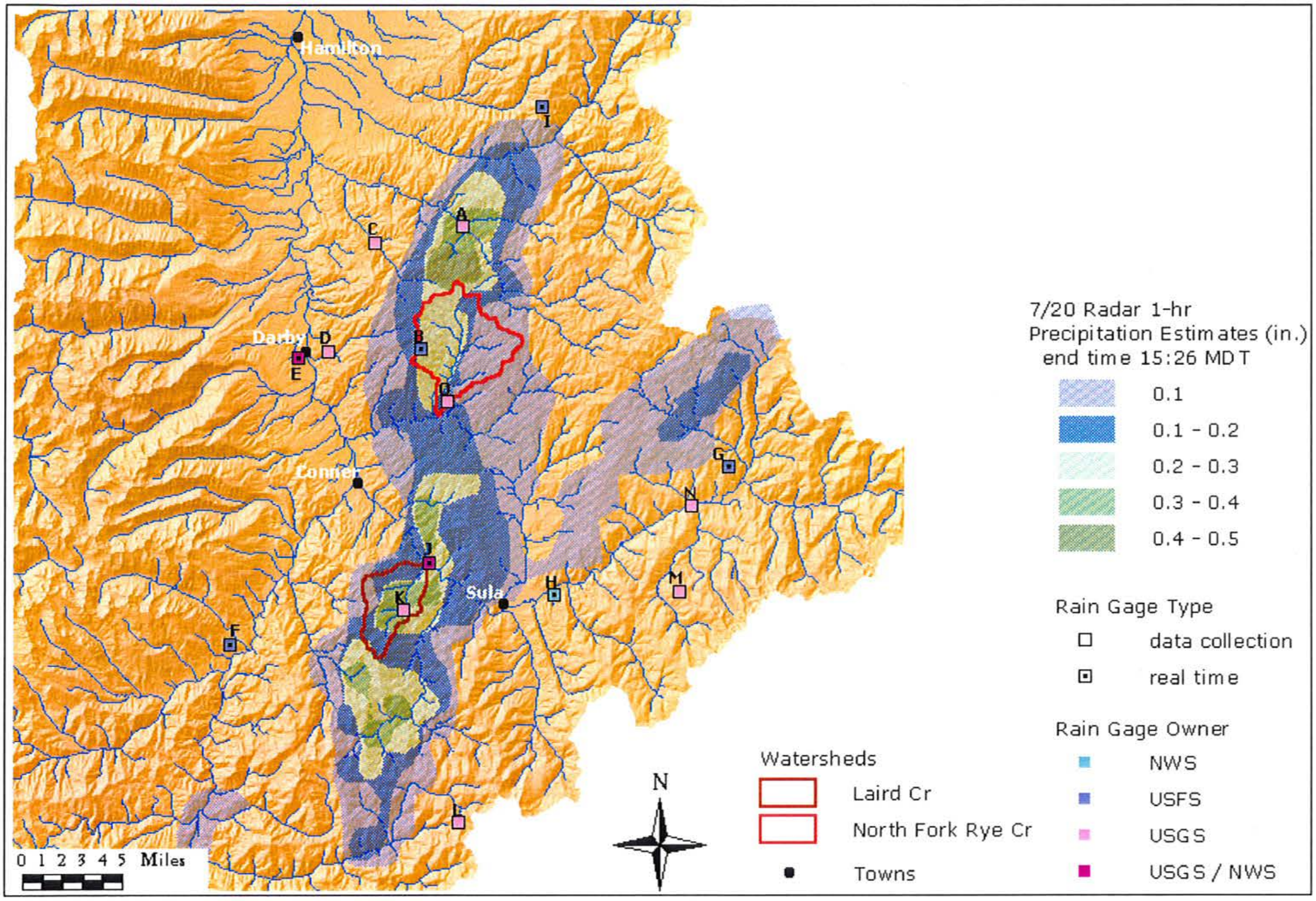


Figure 15. July 20th underestimated one hour radar precipitation amounts compared to 30-minute storm total raingage data in the southern Bitterroots.

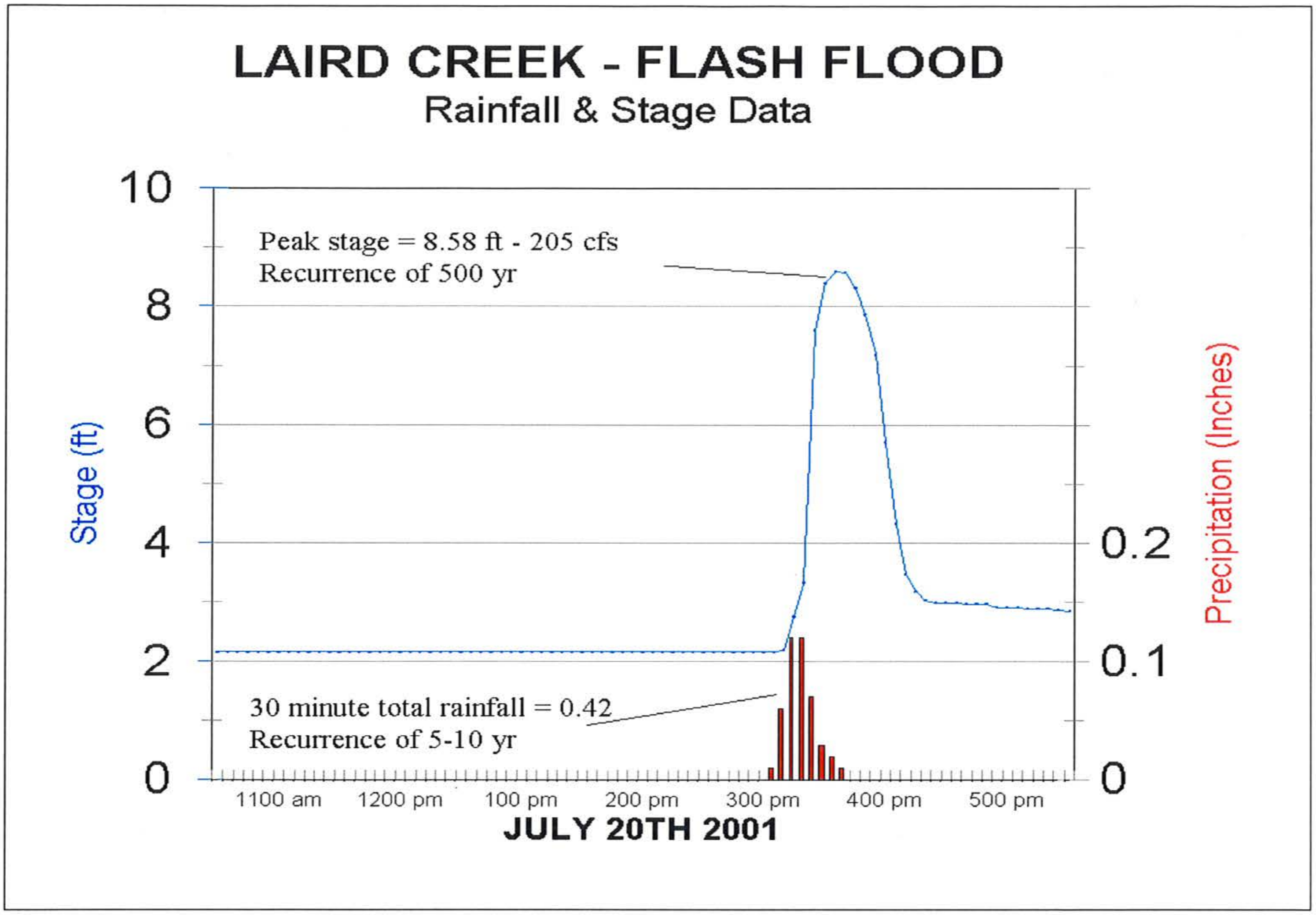


Figure 16. Rainfall, stage and discharge data from the July 20th storm at Laird Creek near Sula, Montana.

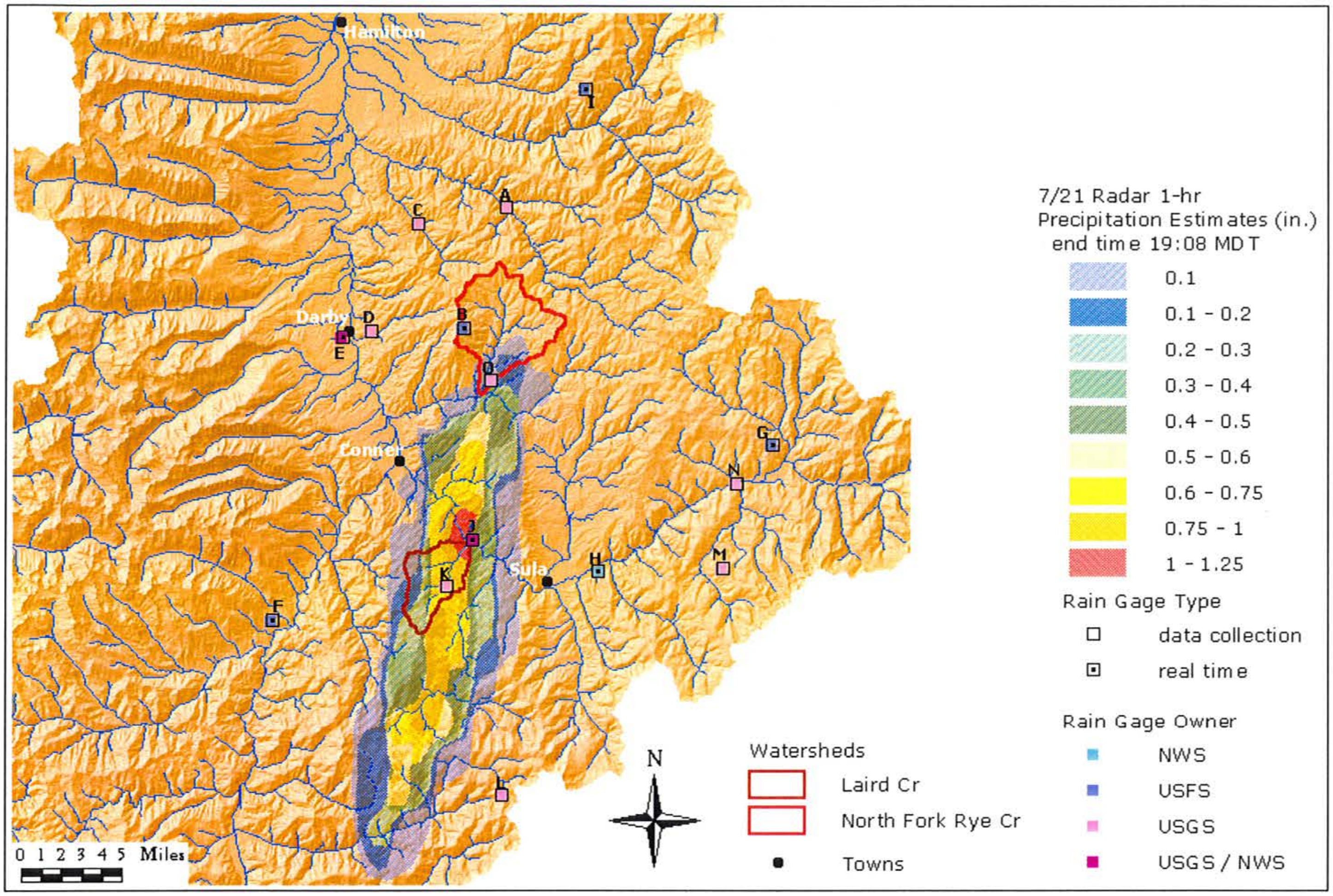


Figure 17. July 21st accurate one hour radar precipitation amounts and 30-minute storm total raingage data in the southern Bitterroots.

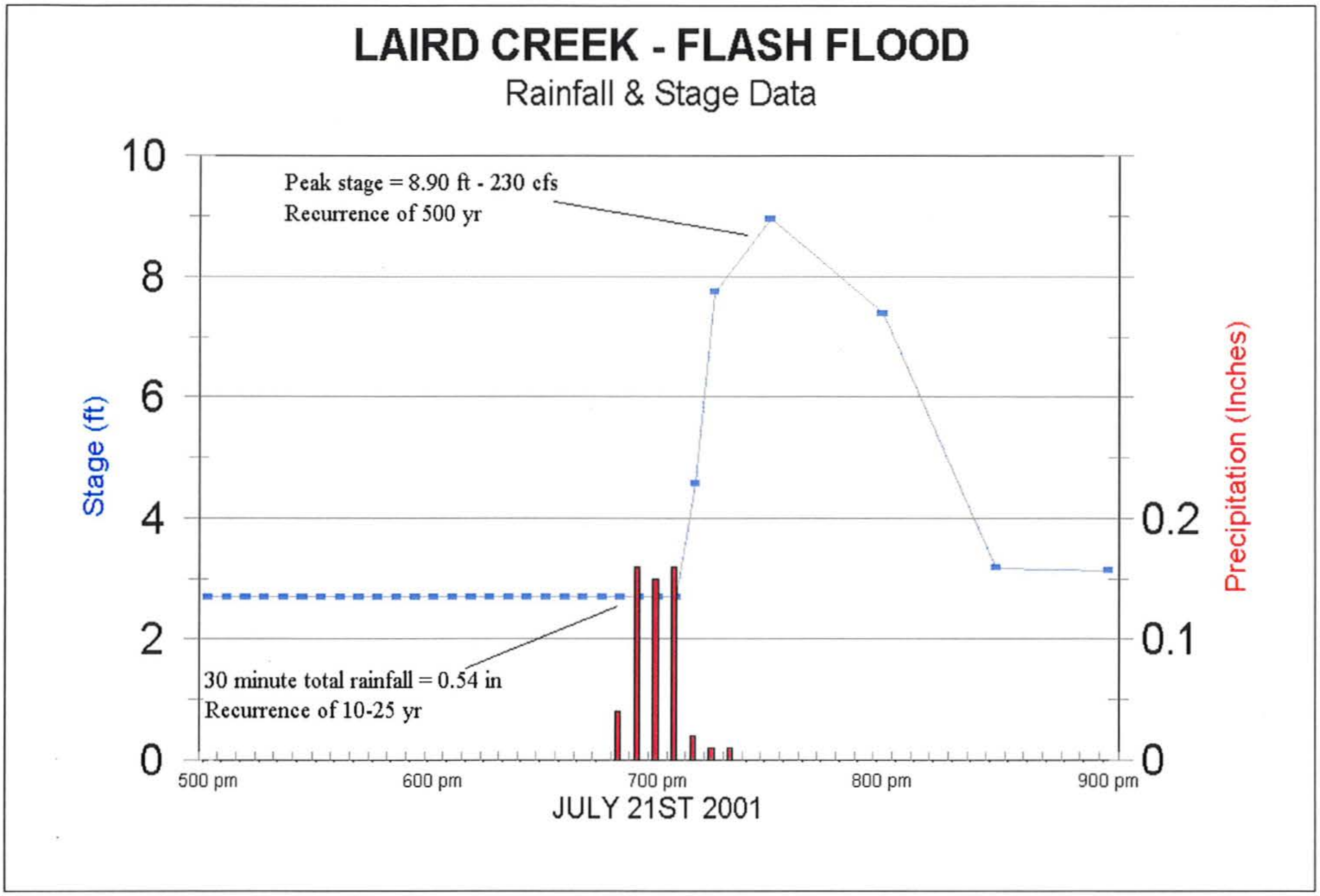


Figure 18. Rainfall, stage and discharge data from July 21th storm at Laird Creek near Sula, Montana.

31 July 2001. An upper level trough matured to a closed low pressure system over southwest Montana on 30 July 2001. This system cooled temperatures below normal with periods of heavier showers and embedded low-topped thunderstorms impacting the burned watersheds. Two day storm total rainfall from the event was an impressive 1.10 inches, although the resulting hydrograph showed only a 0.16 foot rise at the USGS river gage (Figure 19). An analysis of the rainfall rates indicate heaviest amounts fell during the early morning of 31 July 2001 with 0.07 inches from 0000 MDT to 0030 MDT and 0.13 inches from 0030 MDT to 0100 MDT. This left a total of 0.20 inches for a one hour period compared to 0.44 inches and 0.54 inches that occurred in a 30 minute period on the 20th and 21st events.

This comparison indicates that the intensity and duration of the rain event is a more important component to producing flood flows than antecedent conditions. Rainfall associated with thunderstorms in the summer months typically produce high intensity short duration events and a threshold rainfall rate appears to be needed before excessive runoff is generated. Longer duration rain events that do not meet the rainfall threshold do not produce abundant runoff, even when soils are saturated.

RAINFALL EFFECT ON WATERSHED RESPONSE

Rain that fell on 20 July 2001 and 21 July 2001 covered the entire Laird Creek watershed according to data collected from USGS tipping bucket precipitation gages in the middle and outlet of the basin. Doppler Radar also indicated basin area coverage of precipitation (Figures 15&17). The time to peak for the flood hydrographs on the 20th and 21st were 30 minutes (Figures 16&18). The observed time to peak(t_p) from the July 2001 floods differs with that of a computed t_p using Snyders method.. A computed lag time and time to peak as determined by Snyders method using physiographic watershed characteristics can be seen below:

$$t_l = C_t(L_{ca}L)^{0.3}$$

where t_l = the lag time (hr) between the center of mass of the rainfall excess for a specified type of storm and the peak rate of flow

L_{ca} = the distance along the main stream from the base gauge to a point nearest the center of gravity of the basin (mi)

L = the maximum travel distance along the main stream (mi)

C_t = coefficient depending on the basin properties

and $C_t = 1.2$ $L = 5.793$ mi $L_{ca} = 2.579$ mi

$$t_p = D/2 + t_l$$

where t_p = the time from the beginning of rainfall to peak discharge (hr)

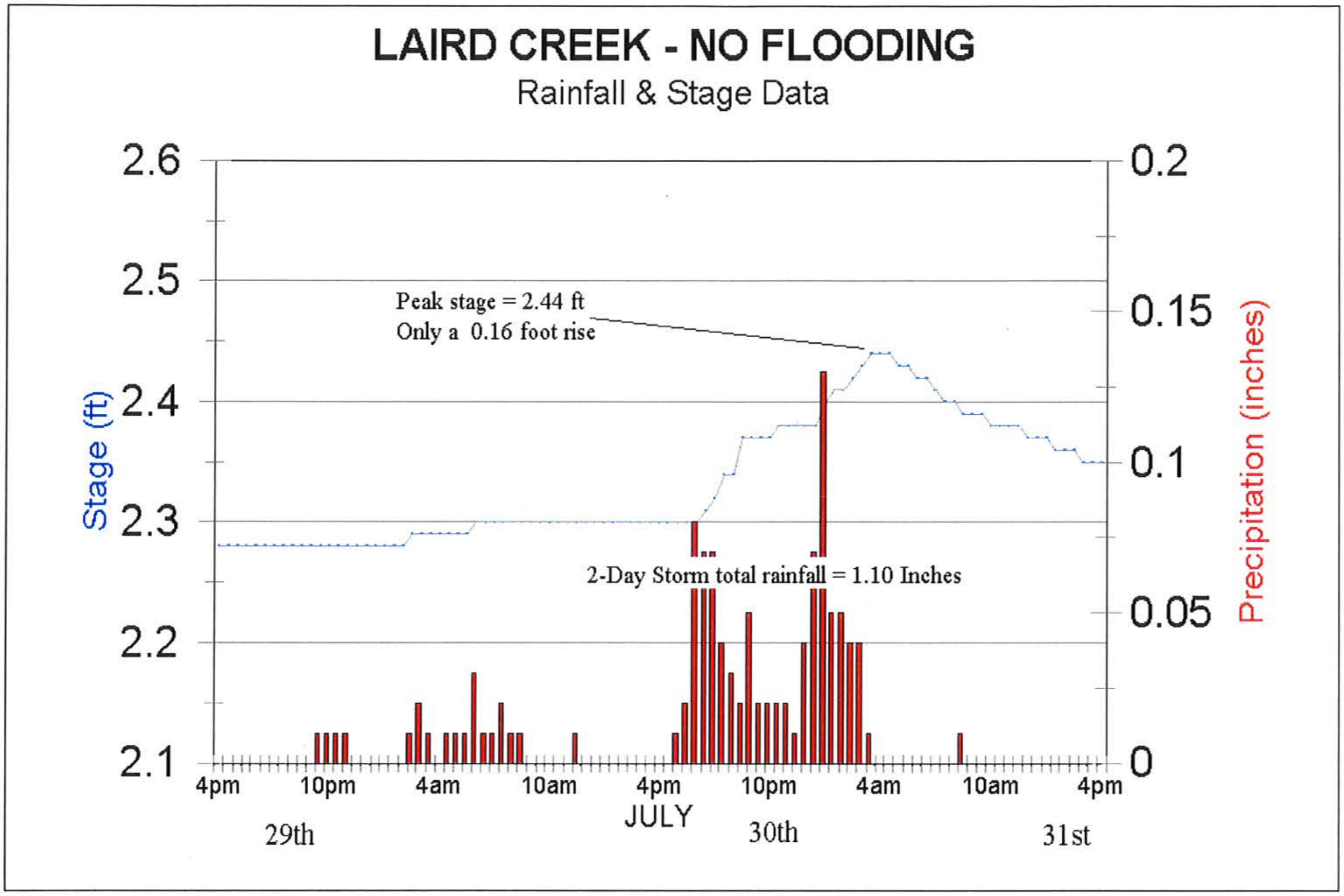


Figure 19. Rainfall, stage and discharge data from July 30th storm at Laird Creek near Sula, Montana.

D = the duration of rainfall (hr)

t_l = the lag time from the centroid of rainfall to peak discharge (hr)

and $D = 30$ min or 0.5 hr $\quad t_l = 2.70$ hr

The relative timing of hydrologic events must be known if drainage areas having subbasins are to be modeled or if continuous simulation is desired (Viessman, Lewis and Knapp, 1989). A basic measure of timing is lag time or basin lag, which locates the hydrograph's position relative to the causative storm pattern (Figure 20 fromViessman, Lewis and Knapp, 1989). It is that property of a drainage area which is defined as the difference in time between the center of mass of effective rainfall and the center of mass of runoff produced (Viessman, Lewis and Knapp, 1989). Time lag is characterized by the ratio of a flow length to a mean velocity of flow and is thus a property that is influenced by the shape of the drainage area, the slope of the main channel, channel geometry, and storm pattern (Viessman, Lewis and Knapp, 1989).

The difference in time to peak between Snyders method (2.95 hrs) and the observed value from the river gage hydrograph (½ hr) can be explained by analyzing the high intensity burn areas and their close proximity to the river gage outlet. A large percentage of high intensity burn was near the basin outlet which produced the majority of the excessive runoff that affected the timing of the hydrograph. A field inspection by the authors revealed large volumes of flows from high burn severity areas in the draws of the lower portion of the watershed and insignificant runoff from areas of medium and low burn severity throughout the watershed (Figure 4).

PRECIPITATION FREQUENCY ANALYSIS

Precipitation frequencies with 24 hour and 6 hour durations are plotted for the state of Montana in the NOAA ATLAS 2 (Precipitation-Frequency Atlas of the Western United States - Volume I-Montana). Rain events that occurred on 20 July 2001 and 21 July 2001 were of 30 minute durations and could not be obtained from the NOAA ATLAS 2 maps, therefore, these values had to be derived from procedures defined in the NOAA ATLAS 2 publication. A one hour value of 1.06 inches and 0.39 inches were determined for the 100 and 2 year storm events respectively using the following equations:

<u>100 yr 1-hr value</u>

$$\boxed{Y_{100} = 0.338 + 0.670[X_1(X_1/X_2)] + 0.001(X_3)}$$

$X_1 = 1.80$ in $\quad X_1$ = 100 yr 6-hr value

$X_2 = 3.00$ in $\quad X_2$ = 100 yr 24-hr value

$X_3 = 42.45$ $\quad X_3$ = elevation (in hundreds of feet)

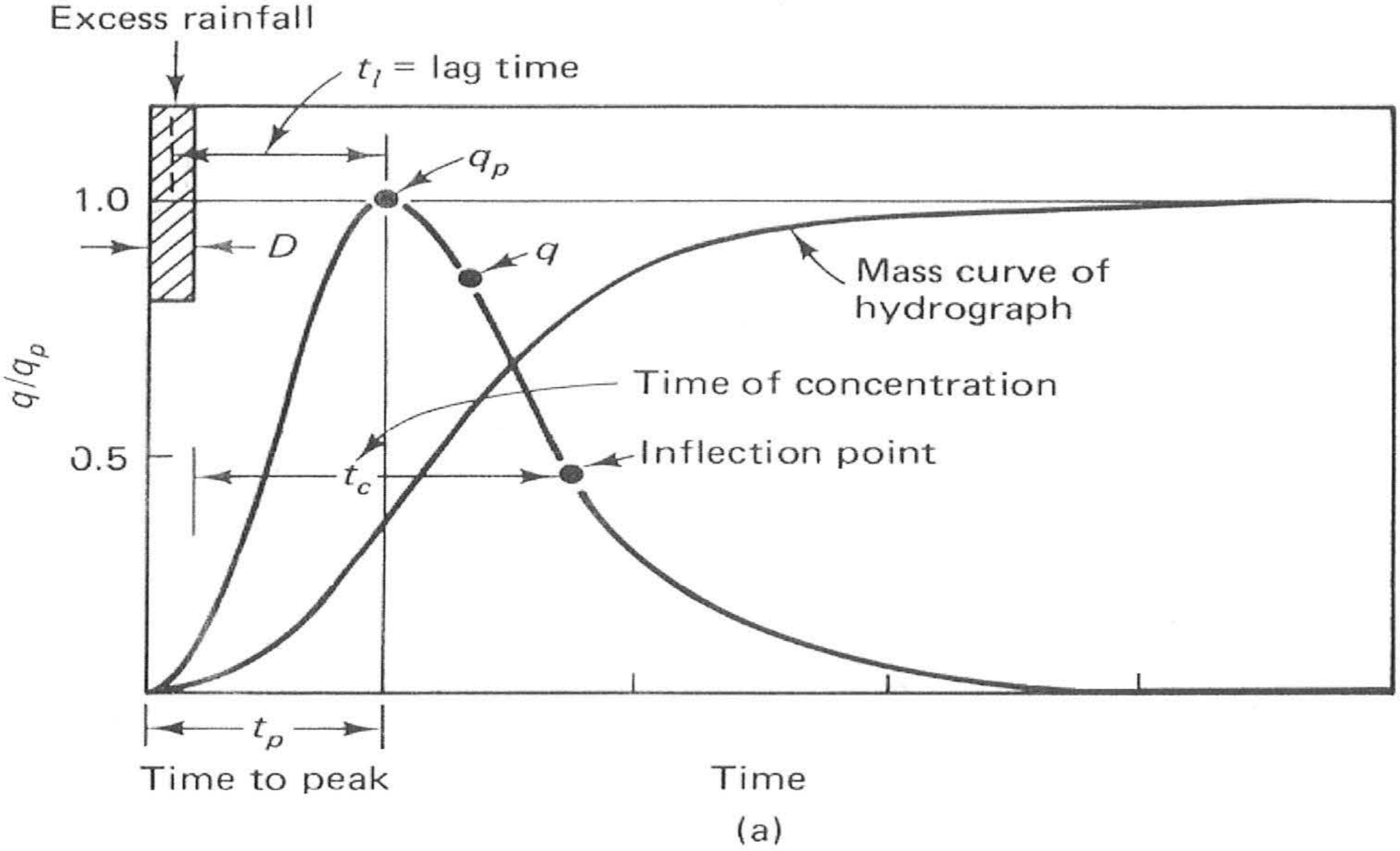


Figure 20. Illustration of lag time and Time to peak from (Viessman, Lewis and Knapp, 1989).

$$Y_{100} = 0.338 + 0.670[1.80(1.80/3.00)] + 0.001(42.45)$$
$$Y_{100} = 1.06 \text{ in}$$

2 yr 1-hr value

$$\boxed{Y_2 = 0.019 + 0.711[X_1(X_1/X_2)] + 0.001(X_3)}$$

$X_1 = 0.80$ in
$X_2 = 1.40$ in
$X_3 = 42.45$

$X_1 = 2$ yr 6-hr value
$X_2 = 2$ yr 24-hr value
$X_3 =$ elevation (in hundreds of feet)

$$Y_2 = 0.019 + 0.711[0.80(0.80/1.40)] + 0.001(42.45)$$
$$Y_2 = 0.39 \text{ in}$$

The Y_2 and Y_{100} values were then plotted on a nomogram (Figure 21) and a straight line drawn between the two points. Values of the 5, 10, 25 and 50 year recurrence interval (table 1) were then estimated from the nomogram (Figure 21).

Table 1. One-hour precipitation values estimated from nomogram in Figure 20.

100yr 1-hr value = 1.06 in	10yr 1-hr value = 0.63 in
50yr 1-hr value = 0.88 in	5yr 1-hr value = 0.52 in
25yr 1-hr value = 0.77 in	2yr 1-hr value = 0.39 in

To obtain ½ hour precipitation frequency values an adjustment factor needed to be applied to the 1-hour values (table 1). The adjustment factor ratio table (table 2) from NOAA ATLAS 2 was used to arrive at final estimates. Rainfall of 0.42 inches on the 20 July 2001 event was compared to ½ hour estimates (table 3) to come up with a recurrence interval of 5-10 years, likewise the 0.54 inches from 21 July 2001 was determined to be a 10-25 year event.

Table 2. Adjustment factors to obtain *n*-minute estimates from 1-hr values

Duration (min)	5	10	15	30
Ratio to 1-hr	0.29	0.45	0.57	0.79

Table 3. Half-hour precipitation values derived from adjustment factors.

100yr ½-hr value = .83 in	10yr ½-hr value = 0.50 in
50yr ½-hr value = 0.69 in	5yr ½-hr value = 0.41 in
25yr ½-hr value = 0.61 in	2yr ½-hr value = 0.31 in

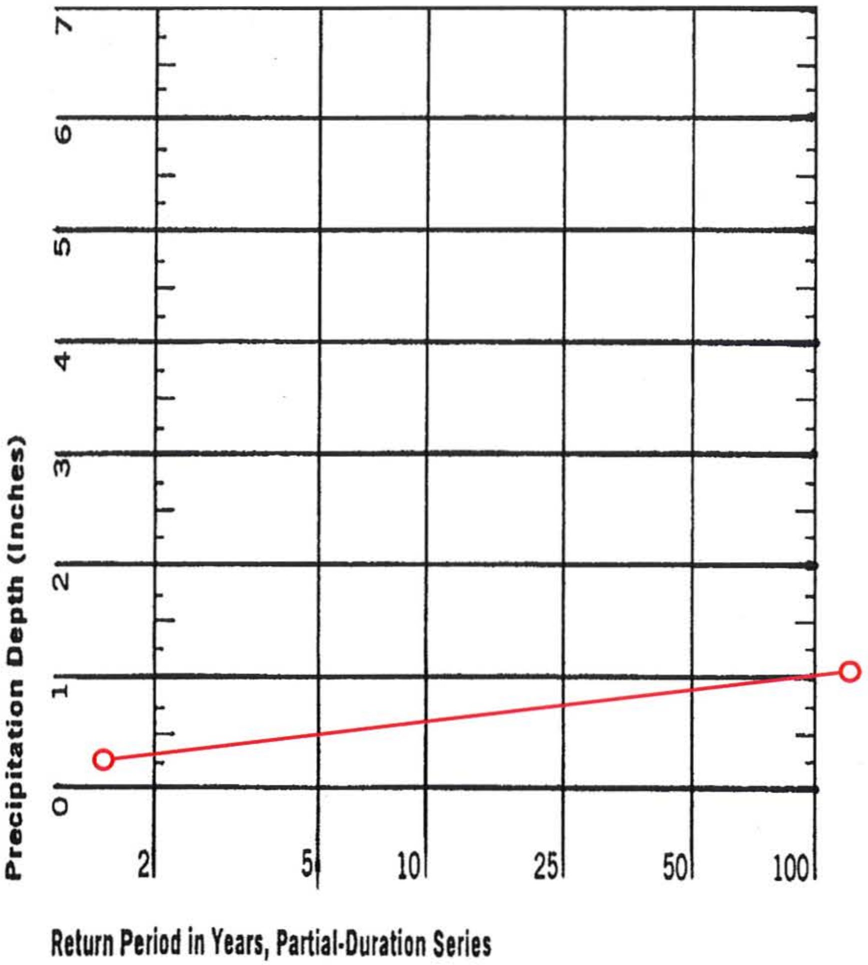


Figure 21. Nomogram expressing precipitation depth versus return period for partial-duration series.

FLOOD FREQUENCY ANALYSIS

Following the rain events in July of 2001 the USGS conducted indirect discharge measurements in many of the watersheds of the Bitterroots. Peak flows on the North Fork Rye Creek were determined to be 230 cfs from the rain event on 15 July 2001. Laird Creek had a computed flow of 205 cfs from the 20 July 2001 event and 230 cfs from the 21 July 2001 event. Provisional regression equations developed by Parrett (2001) were then used to arrive at a recurrence interval for the flows (Parrett, USGS, oral commun., 2001).

GEOMORPHIC PROCESSES

Landscape altering geomorphic processes

Many of the watersheds in the burned areas of the Bitterroot National Forest experienced geomorphic processes during high intensity rainfall events. Rill formation was common, especially at the headwaters of the draws that formed the watersheds. Hyperconcentrated flows and debris flows altered landscapes in many of the drainages and led to the formation of gullies and debris fans at the base of hillsides. These processes also added ash, mud, rock and trees to the flash flood flows that followed the thunderstorms.

Rills

Inspection of individual draws in the watershed revealed a series of rills that formed near ridgetops and steeper slopes as a result of intense rain impacting soils that were affected by high intensity fire (Figure 22). Rill formation was more numerous on hill slopes in the upper elevations of the draws and transported water down the slopes into the center of the draws. Water then became concentrated in the draws and appears to have hyperconcentrated the flow which led to gully erosion and formation (Figure 23). Flows gathered erosive energy as they moved downslope and scoured gullies to granitic bedrock (Figure 23). Tremendous amounts of soil, granitic boulders and trees were transported with the flows which deposited a large portion of their debris in debris fans at the confluence with perennial streams (Figure 24&25).

Hyperconcentrated flow and debris flow

Some questions arise as to the nature of the flows that formed gullies and led to flash flooding in the Bitterroot Watersheds. Were the flows hyperconcentrated flows or debris flows? Costa and Williams, 1984, reported that when poorly sorted soil and rock debris are mixed with a critical amount of water, a dense, structurally coherent slurry forms that can move rapidly down slopes and along channels, causing great destruction. Debris flows resemble wet concrete and usually form as a result of hillslope failure during rainstorms (Costa and Williams, 1984). Flood flows that occurred in the Laird and North Fork Rye Creek watersheds showed no visual evidence of hillslope failure which is commonly associated with debris flows, however, typical debris flow processes were found throughout the watersheds, such as:

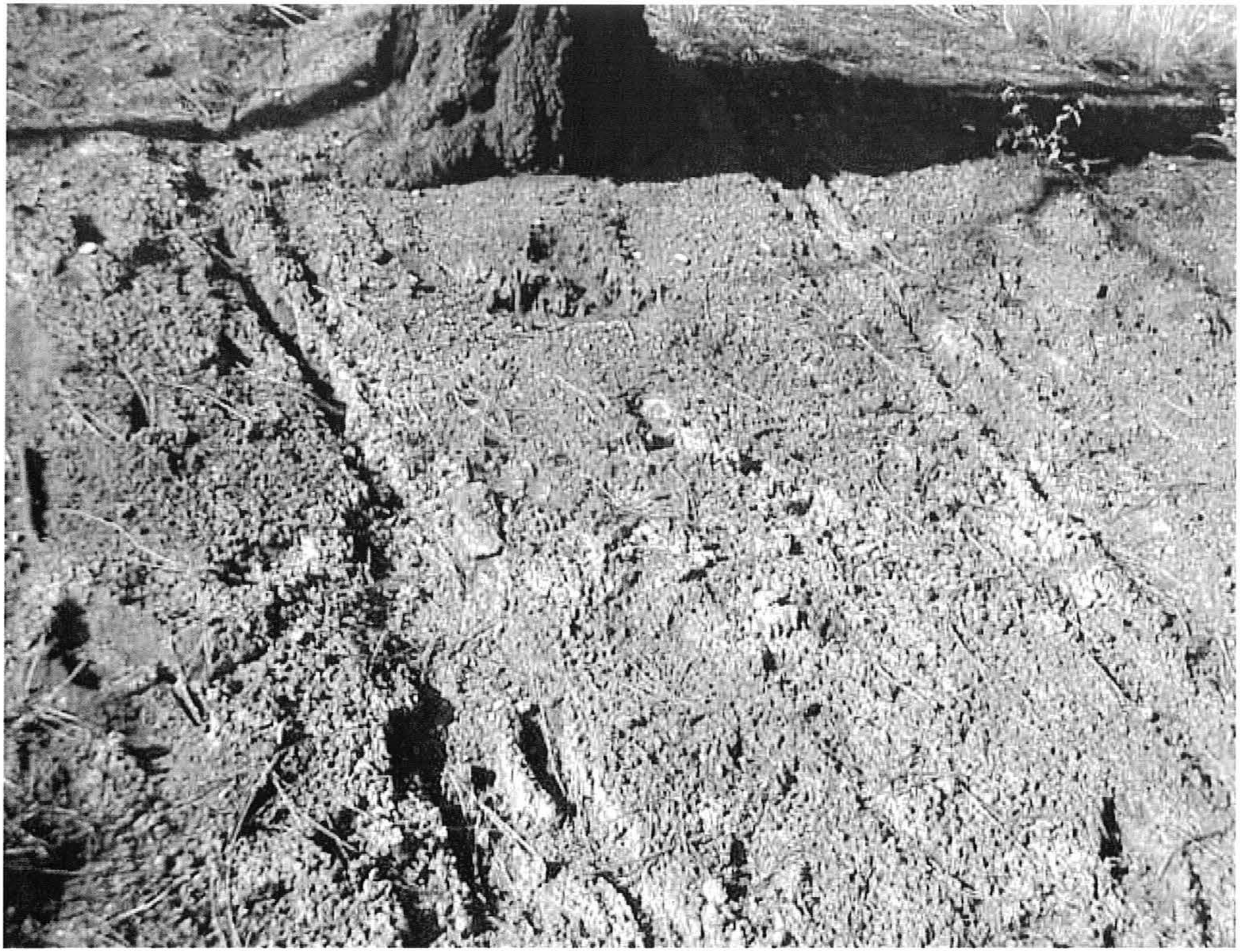


Figure 22. Rills formed in soil on high burn severity areas along the hill slopes

Figure 23. Gully formed by hyperconcentrated flow and debris flow in high severity burn area

Figure 24. Tree and granitic rocks transported by debris flows in high severity burn area.

Figure 25. Debris fan created at base of gullied draw.

- U-shaped gullies and gullies scoured to bedrock
- Larger clasts and boulders transported with the flow
- Debris fans at the base of gullies

Excessive runoff and debris transport from forest fires that have been studied by hydrologists with the USGS indicate the formation of debris flows as a process that typically occurs in high severity burn areas in the western United States. Characteristics that indicate the formation of debris flows do not have to be associated with hillslope failure (oral commun. Cannon and Parrett, 2001).

SUMMARY AND RECOMMENDATIONS

Summary

The southern Bitterroot Valley and surrounding Bitterroot and Sapphire Mountains experience more thunderstorm events each year than any other area of the WFO Missoula CWA. Single-cell thunderstorms over southwest Montana, like those that occurred in July of 2001, can lead to rapid runoff and flash flooding on severely burned watersheds. Under normal circumstances this type of thunderstorm event would not lead to flooding. Radar performance was adequate to assist forecasters in the issuance of NWS flash flood warnings, however OHP products were less than timely due to the flashy nature of burned soils located in steep terrain. Dry valley air is a common element during the summer months in southwest Montana. Elevated thunderstorms with virga and little rainfall occur frequently, leading to rainfall overestimation and faulty comparisons between Doppler OHP and ground truth. Above normal TPW values during the July 2001 flash flood events analyzed in this paper gave forecasters more confidence in radar performance and a heads up on potential flash flooding.

In the Laird and North Fork Rye Creek watersheds roughly 30% of the basin was classified as high burn severity by the USFS. The high burn severity areas were determined to be the greatest threat to produce excessive runoff capable of flash flooding. These areas exhibited over 80% destruction of plant canopy and total incineration of the organic duff layer and baked soils lead to hydrophobic properties. The burned conditions altered watershed response leading to changes in time to peak for the watersheds. A derivation of time to peak using Snyders method based on basin characteristics indicated 2.70 hours to peak while observed streamgage data indicated a 30 minute time to peak.

Rainfall threshold rates that were developed and used by the NWS to predict flash flooding for the three events of July 2001, appeared to work well. However, threshold values that worked for predicting flooding one year after the fires may not work in preceding years. Rainfall should continue to be monitored at burn areas to see if threshold values change as the watersheds recover from forest fire.

Recommendations
Making contacts and working closely with other government agencies and local groups, such as, the USFS, USGS, local law enforcement, county disaster and emergency managers and recruiting volunteer citizens close to burned areas is key to a successful prediction and warning program. Consulting with government agencies in order to obtain additional precipitation and river gage data in remote burn areas is critical to aiding meteorologists and hydrologists in predicting flash flooding. If forest fires occur on USFS land, it is important for NWS personnel to make contact with USFS hydrologists and soil scientists within a week or two after fires have ended in order to get involved in the Burn Area Emergency Rehabilitation (BAER) team.

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APPENDIX

Table 4. Rainfall data from precipitation gages in the southern end of the Bitterroot Valley for July 15, 2001

ID Gage

A Sleeping Child

time	*inches*
15:10	0.01
15:20	0.01
15:25	0.01
15:30	0.03
15:35	0.21
15:40	0.17
15:45	0.15
15:50	0.08
15:55	0.02
16:00	0.02
16:05	0.02
16:10	0.01
16:15	0.02
16:20	0.01
16:25	0.02
16:30	0.02
16:35	0.01
16:40	0.01
total	0.83

ID Gage

B Deer Mountain (1hr data)

time	*inches*
16:04	0.29
17:04	0.05
total	0.34

ID Gage

C Little Sleeping

time	*inches*
15:40	0.01
15:50	0.01
16:00	0.01
16:05	0.01
16:10	0.01
16:15	0.01
16:20	0.02
16:25	0.02
16:30	0.02
total	0.12

D Burke Gulch

time	*inches*
15:20	0.01
15:25	0.03
15:30	0.06
15:35	0.02
15:40	0.02
15:50	0.01
16:00	0.02
16:05	0.01
16:10	0.01
16:15	0.02
total	0.21

E Darby R.S.

no precipitation recorded

F West Fork (1hr data)

time	*inches*
15:03	0.52
16:03	0.32
17:03	0.07
total	0.91

G Tepee Pt

no precipitation recorded

H Sula 3 ENE

no precipitation recorded

I Gird Point (1hr data)

time	*inches*
16:09	0.57
17:09	0.41
18:09	0.11
total	1.09

Table 4. Rainfall data from precipitation gages in the southern end of the Bitterroot Valley for July 15, 2001

ID Gage

J Laird Ck/Hwy 93

time	*inches*
15:15	0.01
15:20	0.14
15:25	0.07
15:30	0.03
15:35	0.03
15:40	0.03
16:15	0.01
total	0.32

ID Gage

K Upper Laird Ck

time	*inches*
15:15	0.08
15:20	0.09
15:25	0.08
15:30	0.05
15:35	0.01
15:40	0.02
15:55	0.01
16:10	0.01
total	0.35

ID Gage

L Little Blue Joint

time	*inches*
14:45	0.02
14:50	0.06
14:55	0.07
15:00	0.01
15:05	0.01
15:10	0.01
16:00	0.01
16:15	0.01
16:25	0.01
16:35	0.01
total	0.22

M Meadow Ck

no precipitation recorded

N Lower Meadow Ck

no precipitation recorded

O North Fork Rye Ck

time	*inches*
15:10	0.01
15:15	0.01
15:20	0.01
15:25	0.09
15:30	0.22
15:35	0.13
15:40	0.05
15:45	0.03
15:50	0.02
15:55	0.02
16:00	0.01
16:05	0.01
16:10	0.02
16:15	0.01
total	0.64

Table 5. Rainfall data from precipitation gages in the southern end of the Bitterroot Valley for July 20, 2001

ID Gage

A Sleeping Child

time	*inches*
15:25	0.01
15:30	0.08
15:35	0.05
15:40	0.01
15:45	0.01
total	0.16

ID Gage

B Deer Mountain (1hr data)

time	*inches*
16:04	0.13
total	0.13

ID Gage

C Little Sleeping

time	*inches*
18:15	0.01
total	0.01

D Burke Gulch

no precipitation recorded

E Darby R.S.

no precipitation recorded

F West Fork (1hr data)

time	*inches*
16:03	0.02
total	0.02

G Tepee Pt

no precipitation recorded

H Sula 3 ENE (24hr data)

time	*inches*
21:00	0.21
total	0.21

I Gird Point (1hr data)

time	*inches*
16:06	0.19
total	0.19

J Laird Ck/Hwy 93

time	*inches*
14:55	0.01
15:00	0.06
15:05	0.12
15:10	0.12
15:15	0.07
15:20	0.03
15:25	0.02
16:10	0.01
total	0.44

K Upper Laird Ck

time	*inches*
14:55	0.03
15:00	0.21
15:05	0.14
15:10	0.03
15:15	0.01
15:30	0.01
total	0.43

L Little Blue Joint

time	*inches*
15:10	0.03
15:15	0.03
15:20	0.05
total	0.11

M Meadow Ck

time	*inches*
15:05	0.01
total	0.01

N Lower Meadow Ck

time	*inches*
15:10	0.01
total	0.01

O North Fork Rye Ck

time	*inches*
15:15	0.03
15:20	0.22
15:25	0.14
15:30	0.01
16:00	0.01
total	0.41

Table 6. Rainfall data from precipitation gages in the southern end of the Bitterroot Valley for July 21, 2001

ID	**Gage**
A	**Sleeping Child**

MDT	*inches*
19:25	0.04
19:30	0.07
19:35	0.16
19:40	0.19
19:45	0.05
19:50	0.01
20:00	0.01
20:10	0.01
20:20	0.01
20:35	0.01
20:50	0.01
21:05	0.01
21:25	0.01
21:45	0.01
22:05	0.01
22:25	0.01
22:50	0.01
23:15	0.01
23:40	0.01
total	0.65

ID	**Gage**
B	**Deer Mountain**
	no precipitation recorded

ID	**Gage**
C	**Little Sleeping**
	no precipitation recorded

D	**Burke Gulch**
	no precipitation recorded

E	**Darby R.S.**
	no precipitation recorded

F	**West Fork**
	no precipitation recorded

G Tepee Pt (1hr data)

MDT	*inches*
17:09	0.06
18:09	0.02
19:09	0.06
22:09	0.07
23:09	0.05
total	0.26

H Sula 3 ENE (24hr data)

MDT	*inches*
18:00	0.27
7/22-18:00	0.22
total	0.49

I Gird Point (1hr data)

MDT	*inches*
20:06	0.22
21:06	0.04
total	0.26

Table 6. Rainfall data from precipitation gages in the southern end of the Bitterroot Valley for July 21, 2001

ID	**Gage**
J	**Laird Ck/Hwy 93**

MDT	*inches*
18:50	0.04
18:55	0.16
19:00	0.15
19:05	0.16
19:10	0.02
19:15	0.01
19:25	0.01
19:35	0.01
19:40	0.01
19:45	0.01
total	0.58

ID	**Gage**
K	**Upper Laird Ck**

MDT	*inches*
18:45	0.08
18:50	0.07
18:55	0.15
19:00	0.03
19:05	0.02
19:15	0.02
19:20	0.01
19:25	0.04
19:30	0.02
19:35	0.02
19:40	0.01
19:45	0.01
19:55	0.01
20:05	0.01
20:15	0.01
20:30	0.01
20:45	0.01
20:55	0.01
21:10	0.01
21:30	0.01
21:45	0.01
22:05	0.01
22:25	0.01
22:55	0.01
23:20	0.01
total	0.61

ID	**Gage**
L	**Little Blue Joint**
	no precipitation recorded

Table 6. Rainfall data from precipitation gages in the southern end of the Bitterroot Valley for July 21, 2001

ID Gage

M Meadow Ck

MDT	*inches*
16:10	0.01
16:45	0.01
16:55	0.01
17:20	0.01
17:25	0.01
17:30	0.01
17:35	0.03
17:40	0.02
17:50	0.01
18:40	0.01
18:45	0.01
18:50	0.02
21:40	0.11
21:45	0.02
21:55	0.01
22:00	0.02
22:05	0.01
22:10	0.02
22:15	0.01
total	0.36

ID Gage

N Lower Meadow Ck

MDT	*inches*
17:05	0.01
17:40	0.01
17:45	0.01
17:50	0.02
19:15	0.01
19:20	0.20
19:25	0.02
21:50	0.04
22:15	0.01
22:20	0.01
22:30	0.01
22:35	0.01
total	0.36

ID Gage

O North Fork Rye Ck

MDT	*inches*
19:15	0.01
19:20	0.03
total	0.04