# A SOUTHWEST COLORADO MOUNTAIN FLASH FLOOD IN AN ENHANCED SOUTHWEST MONSOONAL ENVIRONMENT

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***Abstract***

*Each summer in the United States, the Southwest Monsoon supplies the normally arid regions of the Desert Southwest with moist air from the eastern Pacific Ocean. The latter part of July 1999 was unseasonably wet across southwestern Colorado, with many reporting sites exceeding 200% of normal July rainfall. Saturated soil conditions coupled with heavy convective rains on 31 July 1999 produced a devastating flash flood near Ridgway, Colorado. Most of the flooding occurred in the Dallas Creek Basin of the southwest Colorado mountains, at elevations ranging from about 6,800 feet to 14,150 feet MSL.*

*The convective environment was characterized by a very unstable airmass, weak wind shear, and precipitable water values approaching 170% of normal. A synoptic trigger feature was not distinctly visible on standard height surfaces, but post-event analysis indicated that a weak short-wave trough existed between mandatory levels. The short-wave trough, lingering thunderstorm outflow, orographic forcing, and unique terrain factors all appear to have worked synergistically to create the unusual environment conducive for excessive rainfall in this small river basin. Maximum recorded rainfall on 30 and 31 July 1999 totaled nearly 3.80 inches, exceeding the 100-year rainfall criterion. Multiple tributaries of Dallas Creek received heavy rain, adding more water and exemplifying the need for forecasters to monitor basin precipitation as a whole. The resultant flash flood tripled the previous peak flow on Dallas Creek and, according to eyewitness reports, transformed the normally tranquil (10-foot wide) creek into a 300-foot wide river. Although no deaths or injuries occurred, damage in this relatively unpopulated region approached $1 million. This study describes the synoptic and mesoscale features, as well as significant hydrological and geographical factors that combined to create this record flood.*

## 1. Introduction

On 31 July 1999, thunderstorms with heavy rain caused widespread damage to the small southwest Colorado county of Ouray (Fig. 1), the state's tenth least-populated county. Rainfall exceeding the 100-year event criterion contributed to the damage of nearly two miles of County Highway 24, and Colorado State Highway 62 was undercut in three places by floodwater. This event was part of a series of heavy rain events that affected western Colorado during July. Dallas Creek, a tributary of the Uncompahgre River, swelled to 51 times its normal volume, resulting in the destruction of the waterway's only river gaging station. Four public bridges were damaged, and a fifth was rendered impassable, isolating several families on a nearby mesa and hampering access of emergency vehicles. Total public damage from these storms totaled over $750,000, half of the county's highway budget and nearly a quarter of the entire county annual budget. Private property damages included $100,000 to bridges and structures, and $20,000 to livestock and hay. No fatalities were caused by this event, but seven people had to be evacuated from an inundated barn by a local mountain rescue team. This study identifies the unique meteorological, hydrological, and geographical factors that worked synergistically to create a devastating and financially crippling flood in this sparsely populated region.

## 2. Southwest Monsoon Background

Increased moisture and more frequent thunderstorms in the southwest United States are attributed each summer to the seasonal shift of lower- and mid-tropospheric winds to a southerly direction. Locally, this wind shift and moisture increase is referred to as the "Southwest Monsoon." The Southwest Monsoon is part of a larger circulation pattern, known as the North American Monsoon, which advects moisture north around the western periphery of a Bermuda High. Several studies (e.g., Stensrud et al. 1995; Hansen 1975; Reitan 1957) have shown the primary low-level moisture source of the Southwest Monsoon to be the Gulf of California and eastern Pacific Ocean. The seasonal northward transport of low-level moisture has been partly ascribed to a low-level jet (Tang and Reiter 1984), with the farthest push north observed during the months of July and August (Hales 1974). Several historical flash floods of note along the Front Range of southern Wyoming and northern Colorado, including Big Thompson 1976 (Caracena et al. 1979), Cheyenne 1985 (Glancy and Dasseler 1986), and Fort Collins 1997 (Peterson et al. 1999), have occurred during late July and early August, with each strongly tied to the Southwest Monsoon. A study by Weaver and Doesken (1990) showed that the recurrence probability for a catastrophic severe weather event along the Front

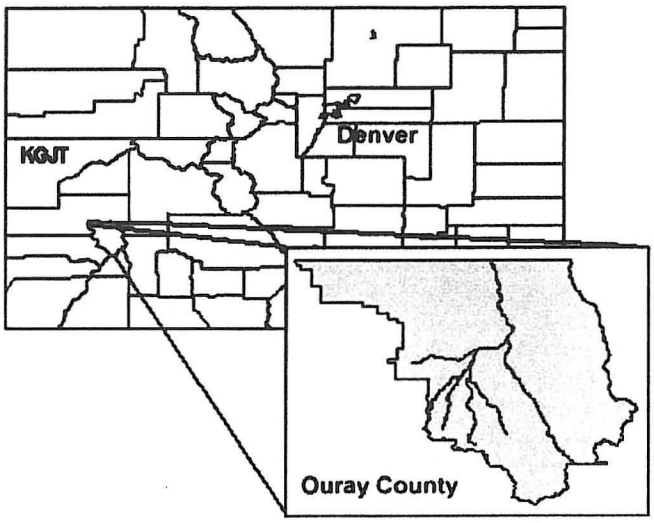


**Fig. 1.** County map of Colorado. Inset is Ouray County, featuring Dallas Creek watershed.

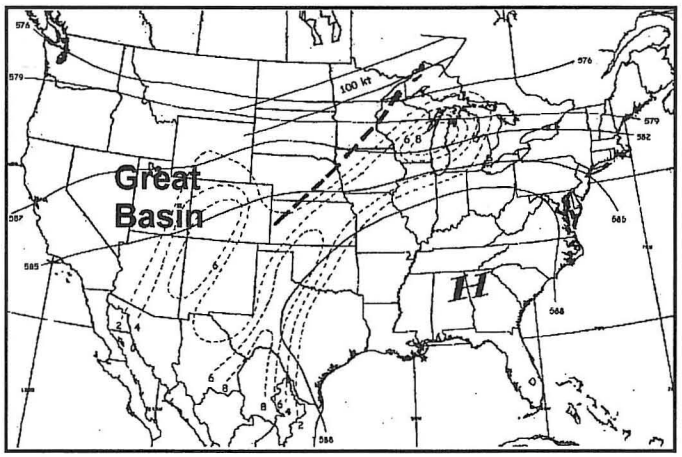


**Fig. 2.** 1200 UTC 31 July 1999 composite analysis. Solid contours represent 500-mb heights (dm), dashed contours are 700-mb isodrosotherms (°C), heavy dashed line shows 700-mb trough, and large arrow denotes 250-mb jet maximum.

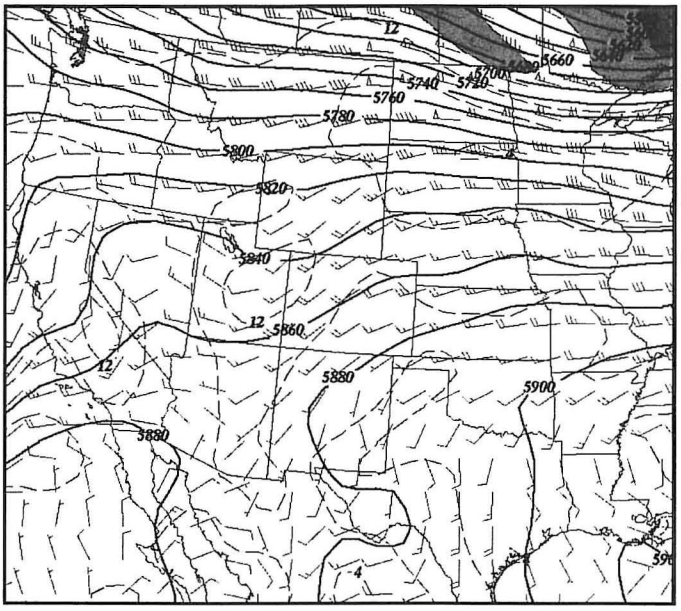

**Fig. 3.** 1200 UTC 31 July 1999 analysis of 500-mb heights (solid, m), absolute vorticity (dashed, $10^{-5}$ $s^{-1}$), and wind barbs (kt).

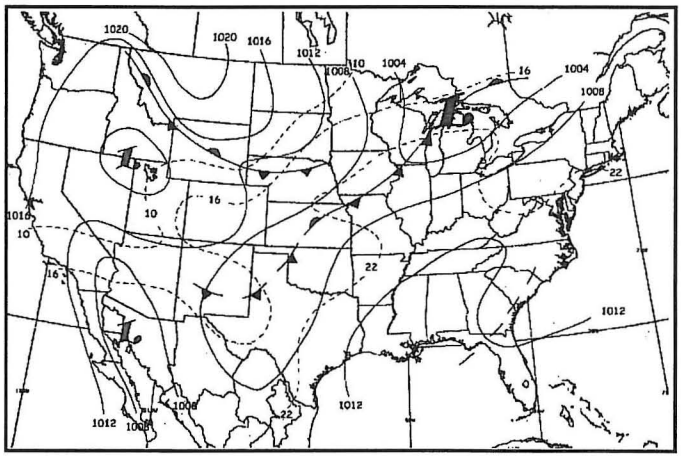

**Fig. 4.** 1200 UTC 31 July 1999 surface composite analysis. Surface frontal symbols are conventional. Solid lines are isobars (mb) and dashed lines are isodrosotherms (°C).

Range was greatest during this period. This is especially likely during very active monsoon seasons. Monsoonal "bursts," the convectively unstable periods of the event, can be particularly wet and prolonged during La Niña years. During cold phases in the eastern Pacific, enhanced tropical activity and intensity associated with La Niña often increase the available moisture for transport into the southwest United States (Bove et al. 1998).

## 3. Synoptic Environment of the 31 July 1999 Event

The 1999 Southwest Monsoon season began in Colorado during the second week of July, with daily convective activity prevalent throughout the southwest corner of the state for the remainder of the month. By the end of July, a prolonged wet period had resulted in near-saturated soils and above-normal stream flows throughout the San Juan Mountains.

On 31 July 1999, the 1200 UTC 500-mb level analysis showed a broad ridge of high heights over the Gulf Coast states, with the western edge extending to west Texas (Fig. 2). Broad zonal flow was present over the northern tier of states, with a diffuse pattern over the Desert Southwest. Examination of lowering cloud top temperatures on infrared (IR) satellite imagery (Fig. 8) indicated a possible east-moving short-wave trough extending from central Wyoming to southern Utah, not evident in the standard 60-meter interval analyses of the 700-mb or 500-mb height fields. However, this feature became more evident using a 20-meter contour interval (Fig. 3). Additionally, tropical moisture was observed moving north from the eastern Pacific Ocean per water vapor imagery and the 700-mb isodrosotherm field (not shown). This synoptic environment displayed characteristics of both the Type I and IV scenarios of western U.S. flash flooding described by Maddox et al. (1980). The surface synoptic pattern (Fig. 4) for the same time indicated no discernable surface front in the Great Basin or surround-

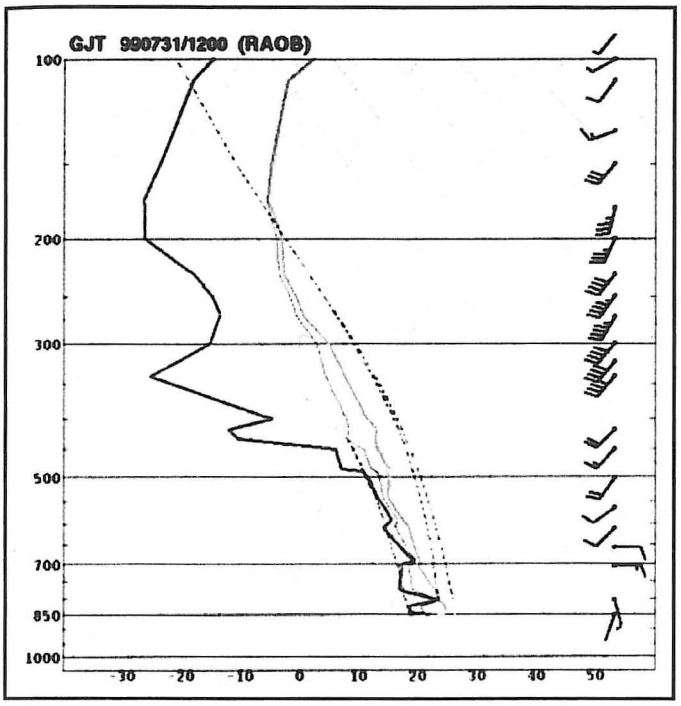


**Fig. 5.** 1200 UTC 31 July 1999 sounding for Grand Junction, Colorado (KGJT). Heavy light and dark grey lines represent temperature and dewpoint, respectively. Wind barbs are in standard notation.

ing region. Surface dewpoints of 57°F to 63°F were in place across southwest Colorado, with surface temperatures only a few degrees higher. The dewpoint values observed in this case were similar to those documented in other devastating western United States flash floods (e.g., Corrigan and Vogel 1993; Knievel and Johnson 1998; Runk and Kosier 1998).

## 4. Mesoscale Characteristics

A number of observing systems were utilized to interrogate the unusual convective environment over southwestern Colorado on 31 July 1999. Regional soundings and wind profilers provided valuable information regarding the highly unstable, weakly sheared environment. High-resolution satellite imagery enabled the detection of an important convergence boundary, and the WSR-88D data revealed the training of slow-moving storms over the Dallas Creek drainage area.

### *a. Thermodynamic structure*

Grand Junction, Colorado (KGJT), located 75 miles northwest of the flash flood region, provided the nearest upper-air sounding data for this case. The 1200 UTC 31 July 1999 KGJT sounding (Fig. 5) indicated unusually high morning instability, evidenced by convective available potential energy (CAPE) of 1683 J $kg^{-1}$ and a lifted index (LI) of -5°C. Utilizing the 79°F maximum temperature observed at Ridgway, Colorado (4.4 miles east of the thunderstorm genesis region) on 31 July 1999 yielded a modified LI of -6°C and a CAPE in excess of 2500 J $kg^{-1}$. The 1200 UTC moisture analysis from the NWS/Hydro-

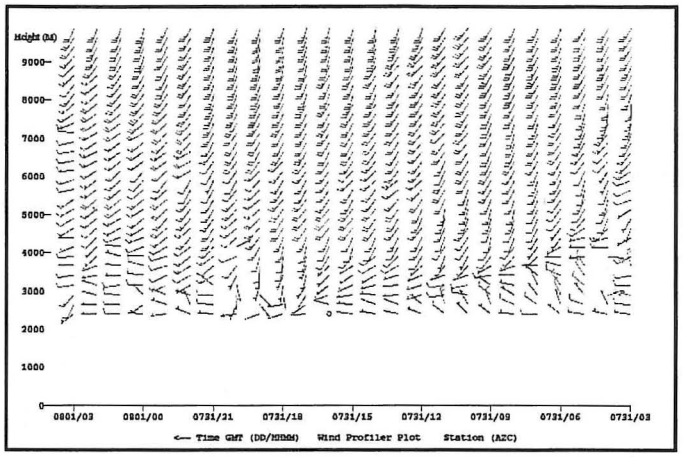


**Fig. 6.** Aztec, New Mexico wind profiler (AZC) data beginning at 0300 UTC 31 July 1999. Time (UTC) increases to the left along horizontal axis. Vertical axis is height above mean sea level (m). Wind barbs are in standard notation.

meteorological Prediction Center (HPC) indicated precipitable water (PW) values of 1.13 inches, approximately 170% of normal. Studies have shown that other devastating flash floods occurring west of the Continental Divide have exhibited similar PW values. A southern Nevada flash flood documented by Runk and Kosier (1998) displayed nearby PW values of 1.04 inches, while a flash flood near Opal, Wyoming revealed representative PW readings of 1.14 inches (Corrigan and Vogel 1993). Moisture below 700 mb increased between 0000 UTC and 1200 UTC 31 July 1999, as indicated by the KGJT soundings. Easterly winds were present in the surface to 650-mb layer on the 1200 UTC 31 July 1999 KGJT sounding. Above this level, winds were representative of the larger-scale flow, uniformly from the southwest through the 250-mb level, with speeds increasing from 10 kt to 45 kt between the 600-mb and 250-mb levels. Weak wind shear of 16 kt was present within the 0-6 km layer. A wind profiler at Aztec, New Mexico (95 miles south of the flood region) confirmed that the shear within this layer remained nearly unchanged through 0000 UTC 1 August 1999 (Fig. 6). Forecasts of storm motion and the mean wind vector indicated the convective environment was favorable for back-building convection against higher terrain to the east. Typical of the mountain-valley wind circulation, it is likely that a diurnal northeast upslope wind would have been present by the time of initial convection. A lack of local wind observations, however, precludes definitive identification.

### *b. Satellite imagery*

The summer of 1999 occurred during a La Niña episode, and was an active period for convection in the eastern Pacific Ocean. Three tropical systems had formed west of Mexico during the week prior to 31 July 1999. Water vapor imagery on 31 July 1999 (Fig. 7) indicated that the Four Corners region was on the western edge of an advancing midlevel to upper-level tropospheric tropical moisture plume associated with these systems.

The aforementioned short-wave trough was evident on satellite imagery moving east from central Utah to the

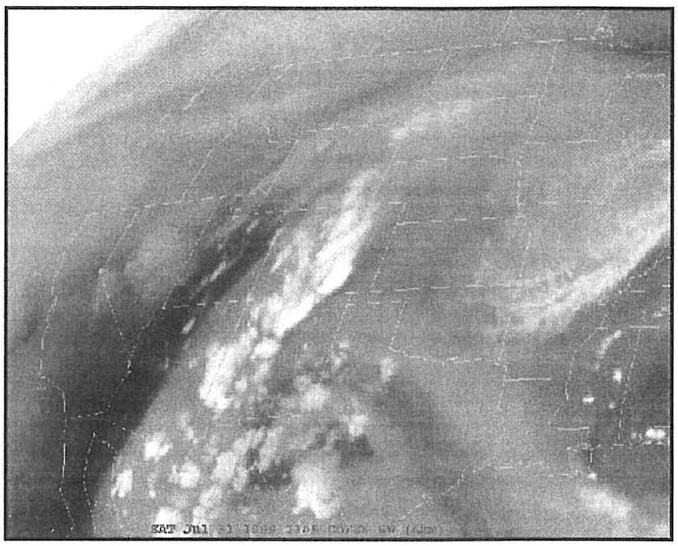

**Fig. 7.** 2145 UTC 31 July 1999 water vapor satellite imagery.

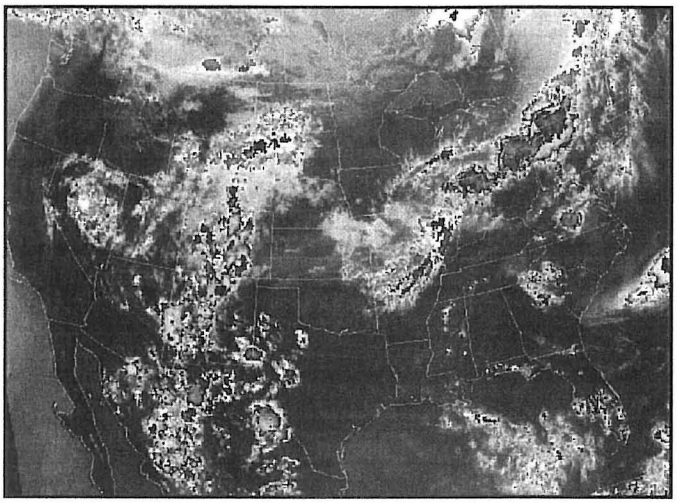

**Fig. 8.** 2145 UTC 31 July 1999 infrared satellite imagery.

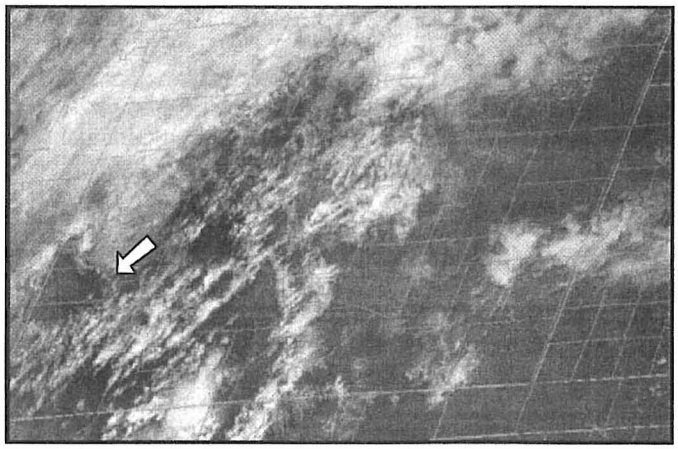

**Fig. 9.** 1715 UTC 31 July 1999 1-km resolution visible satellite imagery. Note outflow boundary over southwest Colorado.

Continental Divide between 1800 UTC 31 July and 0200 UTC 1 August 1999. Minimum convective cloud top temperatures over Ouray County fell in the warm top range of -47°C to -52°C (Fig. 8), and identified closely with the single-clustered thunderstorms described by Spayd and Scofield (1983). The most important feature ascertained through satellite imagery examination was an elongated, quasi-stationary thunderstorm outflow boundary along the Uncompahgre Plateau. This feature was evident in 1-km resolution visible imagery at 1715 UTC 31 July (Fig. 9), and was oriented northwest-southeast on the south side of the plateau.

The trailing edge of the boundary extended southeast to the genesis region of the flash flood-producing thunderstorms, and became the focus for the initial convection. A similar quasi-stationary boundary was found by Runk and Kosier (1998) to be a mechanism that helped initiate convection. In the Dallas Creek case, a large area of subsidence was located west of the genesis region in conjunction with the terrain-anchored outflow boundary. The subsidence region (mesohigh) was formed by rain-cooled air due to early morning thunderstorms that occurred west of Dallas Creek. This cloud-free area lacked subsequent cloud development until the late afternoon hours, well after the onset of nearby convection over the Dallas Creek region. Visible satellite imagery at 2-km resolution indicated that thunderstorm training occurred across the quasi-stationary boundary east of the subsidence field during the time period 1815 UTC to 2315 UTC 31 July. In addition to the outflow boundary and mesohigh, overshooting tops were observed on 2-km resolution visible satellite imagery between 2045 UTC and 2245 UTC 31 July. This approximates the time that the short-wave trough, identified earlier, had tracked through western Colorado. This weak short-wave trough generated additional synoptic lift in the midlevels of the atmosphere, which was focused by the mesocale forcing during this event.

### c. *Radar*

The evolution of the precipitation estimation pattern from the Grand Junction, Colorado WSR-88D (KGJX; located at a height of 10,000 feet MSL, 65 miles north of the flood site) data confirmed that the thunderstorms were regenerating and moving over the same area of western Ouray County. From thunderstorm initiation until approximately 2200 UTC 31 July 1999 the heaviest precipitation was oriented over the drainage region of Pleasant Valley Creek, the northernmost tributary of Dallas Creek. A peak reflectivity of 56 dBZ was observed at 2131 UTC (Fig. 10a) over this basin. The axis of heaviest precipitation and maximum reflectivity then shifted several miles south and east to the West Fork Dallas Creek drainage, another Dallas Creek tributary, after 2200 UTC. The maximum reflectivity noted over this basin was 44 dBZ at 2247 UTC. The times of peak reflectivity corresponded very well with observed maximum rainfall rates over the respective drainage basins. The south and east shift of the heavy rain axis occurred on the right rear flank of the thunderstorm cluster (Fig. 10b). Chappell (1986) described this as the most active section of a storm as it becomes stationary, and the region most likely to cause heavy rain and subsequent flooding. Reflectivity data also indicated that the storms gradually weakened as they moved away from the higher terrain. Low-level boundaries were not discernable through radar

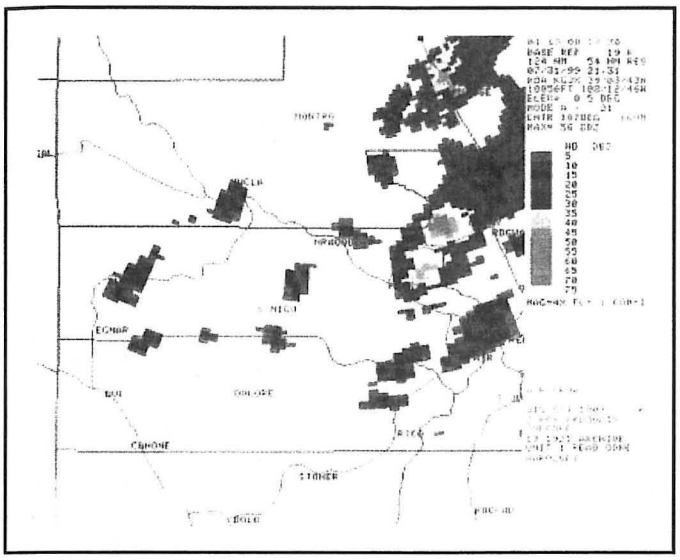

**Fig. 10a.** 2131 UTC 31 July 1999 0.5° angle reflectivity imagery from Grand Junction, Colorado WSR-88D (KGJX).

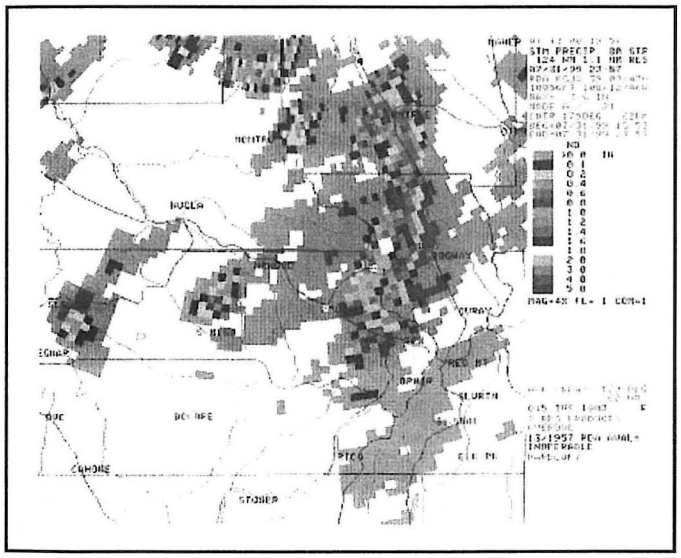

**Fig. 10b.** As in Fig. 10a, except for 2157 UTC storm total precipitation.

reflectivity data due to the elevation of the KGJX WSR-88D and its distance from the Dallas Creek watershed.

## 5. Numerical Guidance

A comparison of the NWS/National Centers for Environmental Prediction (NCEP) nested-grid model (NGM) and Eta model indicated that the NGM provided a better forecast of the monsoonal flow and the weak short-wave trough west of the region. Therefore, only NGM forecasts from the 1200 UTC 31 July 1999 model run are presented here.

Dewpoint analysis at the 850-mb level valid at 1200 UTC 31 July 1999 (Fig. 11) varied from 57°F to 63°F (14°C-17°C) over southwestern Colorado. Figure 12 clearly denotes an equivalent potential temperature ($\theta_e$) ridge at 850-mb level, indicative of residual moisture from recent thunderstorms. The NGM depicted a tight 850-mb $\theta_e$ gradient across western Colorado between 1800 UTC 31 July 1999 and 0000 UTC 1 August 1999. Shi and Scofield (1987) have shown that flash flood producing thunderstorms often form along the $\theta_e$ gradient. Weak low-level convergence over the southwest quadrant of Colorado can also be inferred from the 850-mb wind field shown in Fig. 12. NGM six-hour forecast total precipitation amounts (valid 0000 UTC 1 August 1999) were near one inch in southwestern Colorado. However, the NGM forecast PW values (not shown) of 0.75 to 1.00 inches were lower than the 1.13 inches observed from the KGJT 1200 UTC 31 July 1999

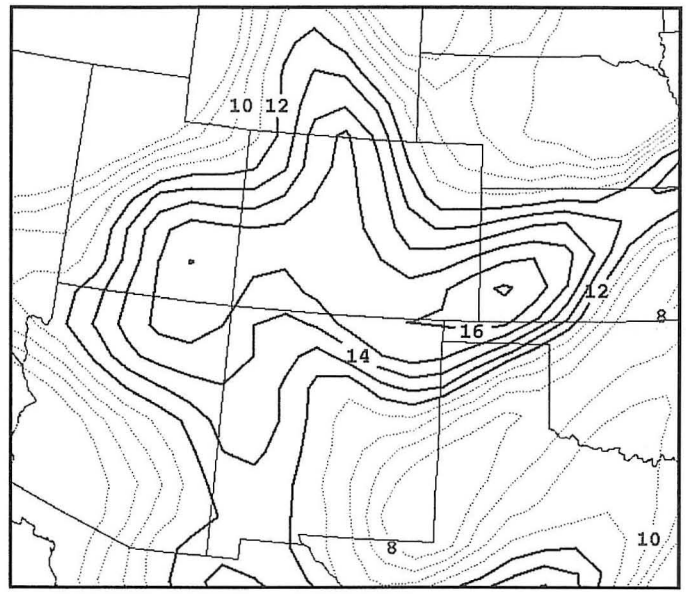


**Fig. 11.** 1200 UTC 31 July 1999 NGM initialization of 850-mb isodrosotherm field (°C).

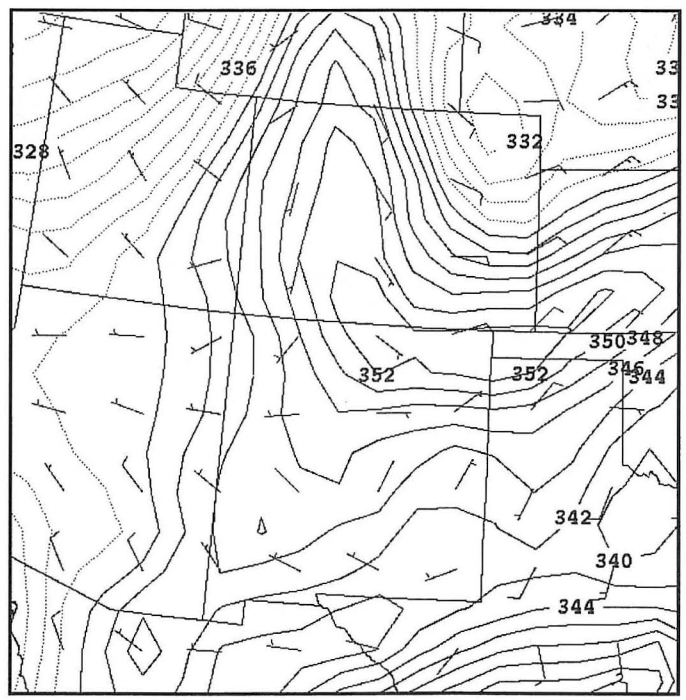


**Fig. 12.** 1200 UTC 31 July 1999 NGM 6-h forecast of 850-mb equivalent potential temperature ($\theta_e$, K) and wind barbs (knots), valid at 1800 UTC 31 July 1999.

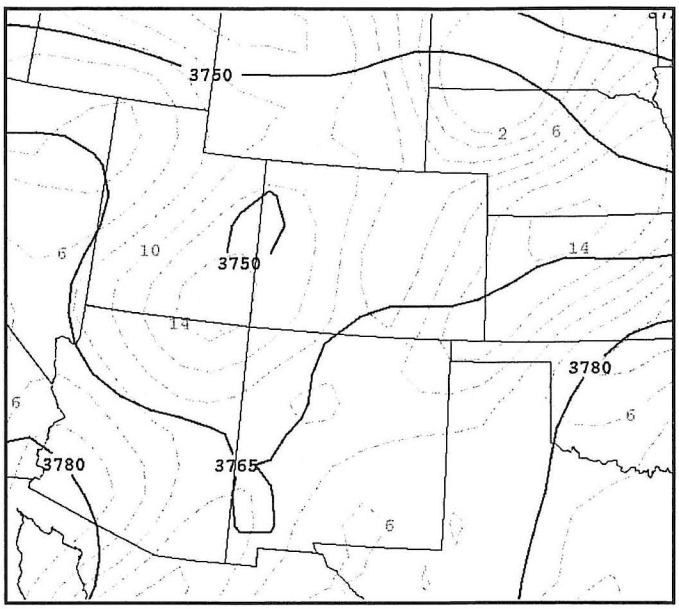


**Fig. 13.** 1200 UTC 31 July 1999 NGM initialization of 650-mb heights (solid, m) and absolute vorticity (dashed, $10^{-5}$ $s^{-1}$).

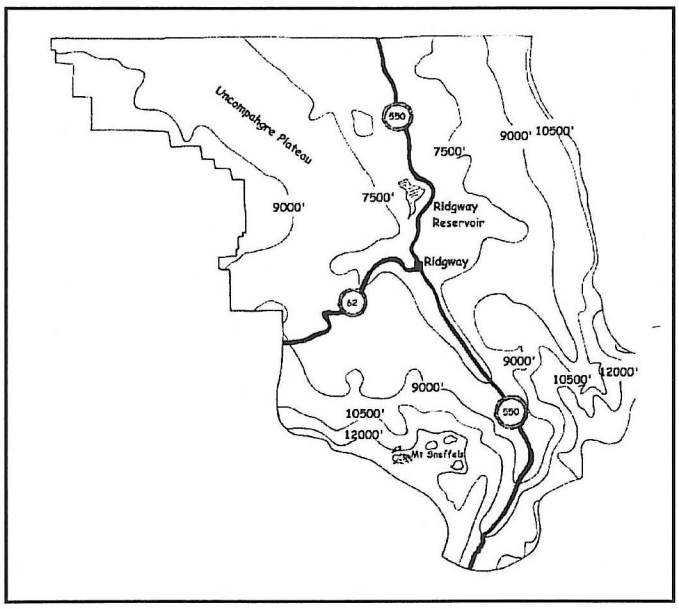


**Fig. 14.** Elevation map of Ouray County, Colorado. Thin solid lines are elevation contours (feet); thick solid lines represent local highways.

sounding. Moderate instability was forecast for the afternoon, with projected LI values of -2°C to -4°C (not shown). This range was less than the LI of -6°C, estimated by modifying the KGJT 1200 UTC 31 July 1999 sounding for the actual high temperature at Ridgway. The weak short-wave trough evident in IR satellite imagery was reflected by the NGM model initialization of 650-mb heights and absolute vorticity (Fig. 13). This feature was forecast by the NGM to traverse western Colorado between 1800 UTC 31 July 1999 and 0000 UTC 1 August 1999. It is important to note that the often-used method of examining the 500-mb vorticity field failed to display this feature. A 700-300 mb or 700-500 mb layer analysis would have likely yielded better identification of the short wave.

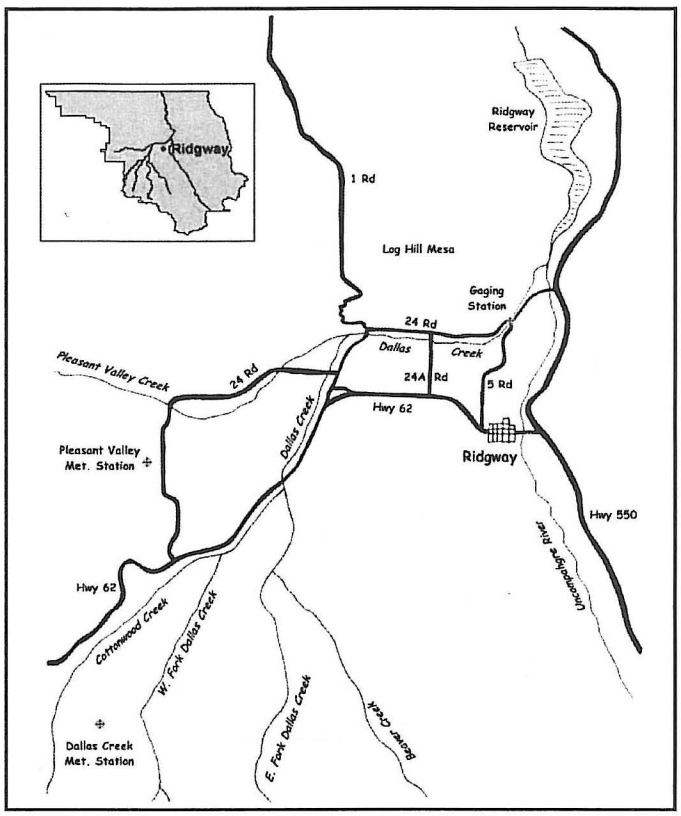


**Fig. 15.** Detail of Dallas Creek watershed. Thin solid lines represent creeks and tributaries; thick solid lines represent local roadways. Inset shows position of Ridgway and Dallas Creek watershed relative to Ouray County.

## 6. Dallas Creek Basin Characteristics

### *a. Topography and vegetation*

Dallas Creek drains 97.2 square miles of land, much of which is in a valley bordered by the San Juan Mountains to the south and Dakota sandstone mesas to the west and north. Basin elevations range from approximately 6,800 feet near the confluence of the Uncompahgre River to 14,150 feet at the peak of Mt. Sneffels (Fig. 14). Vegetation in the higher terrain consists mainly of Ponderosa pine, spruce, pinyon, and juniper. The lower portion of the basin rests upon a large formation of Mancos shale, a slick rock with a high clay content that has a tendency to swell when it gets wet. This soil morphology results in little natural vegetative growth and the valley is used primarily for ranching and the agricultural production of hay.

### *b. Hydrology*

Dallas Creek flows into the Uncompahgre River just upstream from Ridgway Reservoir, and contributes about 20% of the total reservoir inflow. The main stem of Dallas Creek is supported by five tributaries: Pleasant Valley Creek, Cottonwood Creek, West Fork Dallas Creek, East Fork Dallas Creek, and Beaver Creek (Fig. 15). The latter four tributaries drain the higher terrain of the northern San Juan Mountains and merge to form Dallas Creek,

while Pleasant Valley Creek lies along the lower elevations of the valley floor and joins Dallas Creek farther downstream.

Stream measurements are made on the Dallas Creek main stem by a United States Geological Survey (USGS) gage located downstream from Pleasant Valley Creek and 1.5 miles upstream from the mouth. According to the 1998 USGS Water Resources Data publication, the mean annual flow at this site is 40.2 cubic feet per second (cfs), with the highest monthly average (76.6 cfs) occurring in July.

*c. Flood history*

The gaging of Dallas Creek began in 1922 and continued until 1927. The gage was re-established in 1956 and has operated up to the time of this writing. Records of the USGS indicate that flood stage exceedance on this stream has been rare during the period of record, with most (78%) annual peak flows cresting below 500 cfs. Until 1999, the flood of record had been a flow of 1120 cfs occurring in August 1923. This was the only previously recorded crest above 1000 cfs.

Flash flooding and mudslides are common to this region, especially in the higher terrain south of the Dallas Creek basin. According to Chronic (1980), there are four major factors that contribute to the area's high slide potential:

1. Unstable volcanic rocks in the area often contain thick layers of poorly consolidated volcanic ash.

2. These volcanic rocks lie above even less stable Mancos shale.

3. Valley walls are over-steepened by past glaciations.

4. This region is subject to thunderstorms and heavy snows that saturate the soil and underlying rock formations.

The capability for flash flood monitoring in this area is good. Radar coverage is adequate and the United States Bureau of Reclamation (USBR) has established an extensive rain gauge network in this basin for the support of Ridgway Reservoir. Ten automated meteorological stations with attached data collection platforms (DCPs) are located between the reservoir and the headwaters of Dallas Creek and the Uncompahgre River.

## 7. Hydrological Impacts

The 1999 Southwest Monsoon season began in western Colorado during the second week of July. In the San Juan Mountains, thunderstorm activity increased dramatically thereafter. Due to an increased flow of moist air from the eastern Pacific Ocean and the recycling of previous thunderstorms in Arizona and New Mexico, precipitable water values were above normal for much of the month. Cooperative observing stations around the Dallas Creek area reported measurable precipitation nearly every day during the last half of the month. Total July

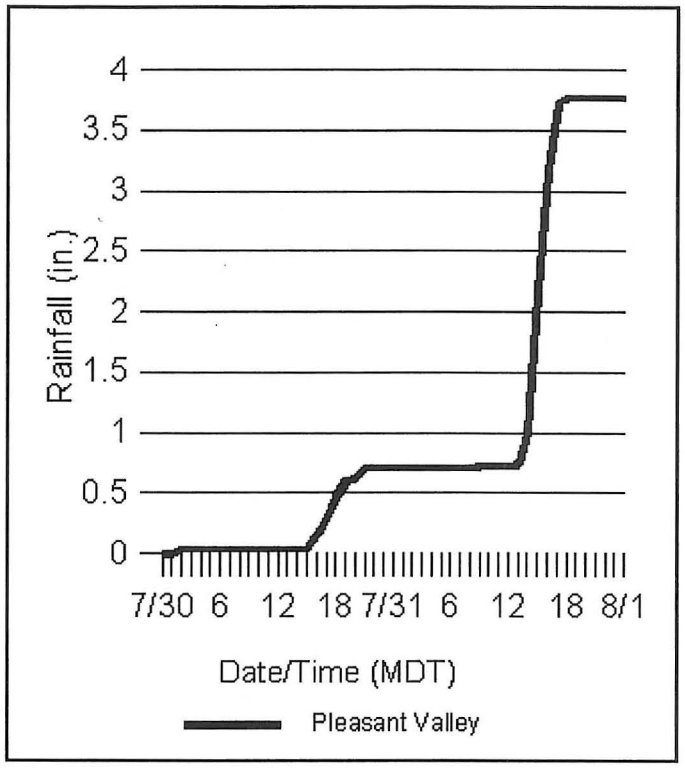


**Fig. 16.** Precipitation (inches) recorded at Pleasant Valley Creek Meteorological Station for the period 0600 UTC 30 July 1999 to 0600 UTC 1 August 1999.

rainfall was in excess of 200% above normal at several sites in southwest Colorado. Telluride, just south of the Dallas Creek basin, measured a monthly total of 6.29 inches (250% of normal), setting a July record. The period of heaviest July rainfall in the Dallas Creek basin occurred during the last week of the month. Thunderstorm activity with heavy rain was observed in or near the basin each day, and numerous mudslides were reported in the adjacent San Miguel River basin to the southwest.

The heaviest rain in this area fell on 30-31 July, a period with precipitable water values in excess of 130% of normal. Placerville, located a few miles to the southwest of the Dallas Creek headwaters, measured 3.13 inches of rain on 30 July 1999 alone. Two of the ten USBR DCP meteorological station rain gauges in the Dallas Creek drainage area also reported heavy rain on 30 July 1999, with even heavier rain the following day. Pleasant Valley Meteorological Station, at an elevation of 7,530 feet MSL in western Ouray County, is located in the drainage of Pleasant Valley Creek. The West Fork Dallas Creek Meteorological Station, located in southwest Ouray County at an elevation of 9,260 feet MSL, is representative of rainfall that falls into both Cottonwood and West Fork Dallas Creeks.

The Pleasant Valley Meteorological Station received 3.77 inches of rain from thunderstorms on 30-31 July 1999 (Fig. 16). Rainfall during this 48-hour period accounted for 72% of the July total. This site was located nearest the axis of heavy precipitation on 31 July 1999, based on radar images and local reports. With nearby

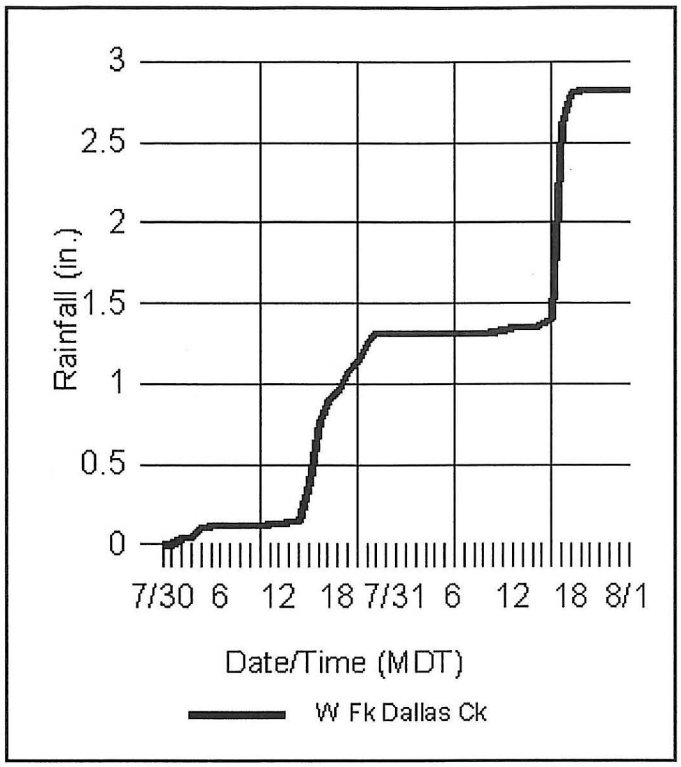


**Fig. 17.** As in Fig. 16, except for West Dallas Fork Meteorological Station.

soils at or near saturation, 1 in. $h^{-1}$ rainfall rates were observed between 2000 UTC and 2200 UTC 31 July 1999. After this time rainfall rates decreased to 0.5 in. $h^{-1}$, before ending around 0000 UTC 1 August. A total of 2.75 inches was recorded between 2000 UTC and 2300 UTC 31 July, an amount in excess of the 100-year rainfall criterion for that location. The diminishing rainfall rates at Pleasant Valley Meteorological Station were a result of a slight south and eastward progression of the heavy rain band. The West Fork Dallas Creek Meteorological Station, approximately 7 miles south of Pleasant Valley, recorded only light amounts of rain through 2200 UTC 31 July 1999. Heavier rain totaling 1.31 inches had fallen at this gauge on 30 July 1999, and surrounding soils were also at or near saturation. After 2200 UTC 31 July, additional heavy rain began to fall, with 1.21 inches recorded at the site by 2300 UTC (Fig. 17). The meteorological stations located near the easternmost tributaries, Beaver and East Fork Dallas Creeks, reported less than 0.25 in. during the afternoon of 31 July 1999.

With rainfall rates exceeding 1 in. $h^{-1}$ for two hours in Pleasant Valley, combined with already saturated soils, Pleasant Valley Creek came out of its banks. Local reports and damage patterns in surrounding hayfields indicated that a large volume of overland flow swept across the valley and inundated the normally tiny stream. The post-flood debris field near the Route 24D bridge indicated that the creek, normally only a few feet across, swelled to over 100-feet wide. This bridge, about 12 feet above the streambed, sustained moderate damage when, according to eyewitnesses, it was overtopped by water levels that extended nearly three feet above the bridge surface.

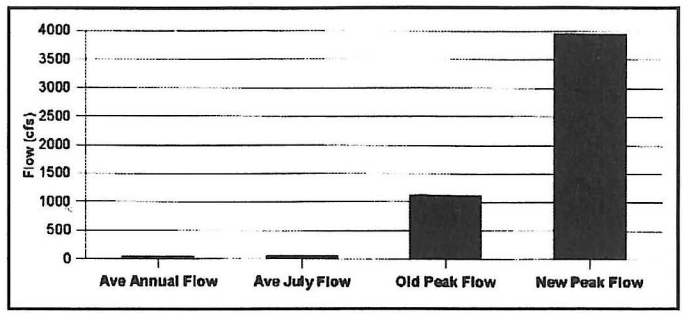


**Fig. 18.** Average annual, average July, and peak flows (cfs) recorded at Dallas Creek (DCKC2) gaging station.

As the heavy rain shifted south, Cottonwood and West Fork Dallas Creeks also became inundated and came out of their banks. The water from these two creeks was forced into the Dallas Creek main channel, which merges with Pleasant Valley Creek about two miles downstream. Downstream from this confluence, the main stem Dallas Creek, normally 8 to 12 feet wide, expanded to 200-300 feet across. A concrete bridge on Route 24A that traverses the creek about one mile downstream from the Pleasant Valley Creek confluence was undercut and damaged.

At the onset of this flood event, the flows on Dallas Creek were averaging between 130 and 140 cfs, nearly double the monthly normal due to recent thunderstorm activity. By 2200 UTC 31 July 1999, telemetered data from the USGS stream gauge indicated that the flow had risen to around 250 cfs. One hour later, the water volume doubled to over 500 cfs. By 0000 UTC 1 August 1999, flows on Dallas Creek had increased to nearly 1,900 cfs, exceeding the old 1923 record of 1,120 cfs. Water levels continued to rapidly increase until 0045 UTC 1 August when all data from the gauge ceased. Estimates through floodmarks by the USGS indicated that Dallas Creek peaked around 3,960 cfs, at a stage of 8.42 feet. This volume of water was 354% greater than the previous 1923 flood of record, and over 5,100% of the July average flow (Fig. 18).

## 8. Discussion and Conclusions

This event exemplified the need to monitor entire basins during potential flash flood scenarios. It is not enough to take into account rainfall over a main channel or waterway; rather, all affected tributaries and drainage channels must be regarded. In this case, it appeared that heavy rain over multiple waterways, which combined into one, played a large role in the overall flooding situation. Also, the Dallas Creek basin floor is composed of a rock surface well-known for its association with flash flooding and debris movement during very wet episodes. In mountainous terrain, where detailed flash flood guidance is rarely available, it is imperative that the flash flood forecaster is aware of the local geology and its particular flash flood characteristics.

The influence of the complex terrain surrounding the Dallas Creek Drainage cannot be underestimated. The Uncompahgre Plateau played a significant role in stalling the lingering thunderstorm outflow boundary.

Additionally, with weak southerly flow aloft, the thunderstorms moved slowly north off the San Juan Mountains (located south of the drainage) where the thunderstorms regenerated over the higher terrain. Knowledge of the local topography can aid greatly in accurately forecasting movement and effects of thunderstorms, especially within small basins.

Post-storm analysis also suggested that the orientation of the rainfall band with respect to the basin, area geology, and rainfall rates all played critical roles in this event. The mesoscale environment exhibited a classic flash flood scenario, where new thunderstorm formation occurred downstream through the basin. Three of the five main tributaries of Dallas Creek experienced similar rainfall amounts of one to two inches in a short period of time. While this amount of rain in any one of the streams probably would not result in the damage seen in this case, the volume of the combined water of three individual merging streams exacerbated the situation.

Operational forecasters need to be astutely aware that conventional analysis of mandatory pressure surfaces may fail to detect significant meteorological features. In this case, model forecasts of standard 500-mb level heights and absolute vorticity failed to capture the shallow short-wave trough at 650 mb that enhanced the convective environment on 31 July 1999, though infrared satellite imagery indicated its presence. Due to the potential for heavy rainfall, identification of these weak features becomes increasingly important in a moist environment, especially when PW values are very high. Even minor short-wave troughs that approach the U.S. Southwest Monsoon environment can result in organized thunderstorm development and increased flash flood potential. The utilization of cross-sections and time-height sections available to the forecaster was vital. Through an examination of satellite data, it was evident that an early morning thunderstorm outflow boundary was the primary focus for initial convective development over the Dallas Creek drainage. It is imperative to carefully monitor the location of these boundaries and other mesoscale convergence zones in order to forecast the onset of convection (and possibly strong thunderstorms).

The Colorado population has started to boom, with much of the new growth seen in the mountainous regions. Flash floods will have an increased societal impact across the region if this trend continues. This creates an even greater forecast challenge as flash flood events in the western United States usually occur with considerably smaller rain amounts than those in the eastern portion of the country (Maddox et al.1980). Due to the sparsity of flash flood guidance in mountainous terrain, western forecasters often use the "one inch or more of rain per hour" rule-of-thumb to quantify flash flood potential. However, this rate of rainfall does not always result in flash flooding. Flash flood environments are often characterized by weak flow and forcing, and subtle features like weak, slow-moving short-wave troughs may be difficult to identify, but can play critical roles. Additionally, factors such as geology, slope, vegetation, and antecedent conditions of affected basin drainages need to be considered in addition to rainfall rate and a general knowledge of meteorological characteristics that produce localized flash flooding.

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