11.3 Decision Support Service and Impacts Associated with the Devastating Flash Flood in Moapa Valley, Nevada

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1. INTRODUCTION

An extreme rainfall event (Stevenson and Schumacher 2014) occurred across the Moapa Valley, Nevada, area on 8 September 2014, causing substantial flash flooding of several washes and the Muddy River. Moapa Valley is approximately 72.4 km (45 miles) northeast of Las Vegas (Fig. 1). Rainfall totals indicated by the Clark County Regional Flood Control District rain gauge network and estimated by the National Weather Service (NWS) Weather Surveillance Radar, 1988, Doppler (WSR-88D) radar analyzed an isolated area to be greater than a 1000-year event (0.1% annual probability) when looking at a 3-hour duration.

Flash flood warnings were issued by the NWS well in advance of flooding reports. Heightened wording, such as *flash flood emergency*, was used in a flash flood warning statement once the most severe flash flood impacts began. Recognizing extreme events as they unfold and providing severity-based product wording has been highlighted by several NWS service assessments (NWS 1999, 2010, 2011). There were several swift-water rescues, major damage to the Interstate 15 corridor system, as well as Clark County infrastructure and residential damages due to this extreme event, as flood waters flowed from generally north to south.

This case study provides a meteorological overview of the 8 September 2014 event, discusses decision support services provided by the NWS in Las Vegas, and highlights the societal and economic impacts across Moapa Valley. Section 2 provides the meteorological overview of the flash flood event. Section 3 discusses various rainfall estimation methods. Section 4 provides an overview of NWS Las Vegas products and services. Section 5 highlights the societal and economic impacts, while section 6 discusses conclusions that can be made from this event.

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2. METEOROLOGICAL ANALYSIS

2.1 *Synoptic analysis*

Meteorological data from this event were obtained and analyzed for 8 September 2014, as well as the days leading up to the event. This section will discuss these data and determine what factors led to this event that produced extraordinary amounts of rainfall in short order. Section 2.1.1 will discuss the synoptic and sub-synoptic features that factored into the severity of this event. Section 2.1.2 will discuss the role that predecessor rain events (PRE's) played leading up to and during the event.

2.1.1 *Environmental Setup*

The Moapa Valley flood of 8 September 2014 was characterized by the anomalous amount of moisture available across the region, courtesy of the remnants of Hurricane Norbert in the Eastern Pacific Basin and Tropical Storm Dolly from the Atlantic Basin. Tropical Storm Dolly made landfall near Tampico, Mexico on the evening of 3 September 2014. The location of the subtropical high (Fig. 2) was critical in helping to transport Dolly's remnant moisture northwestward into the Desert Southwest ahead of Hurricane Norbert and an approaching upper level shortwave trough off of the Pacific Coast. As a result, the 12 UTC and 00 UTC NWS Las Vegas observed soundings from 8 and 9 September set precipitable water records of 41.15 mm (1.62 inches) and 44.20 mm (1.74 inches), respectively, which are over three standard deviations above normal for early September (Fig. 3). The close proximity of the temperature and dewpoint profiles through the lower and mid-levels of the sounding indicated that precipitation efficiency would be high with any convection that developed across the area. Several environmental factors led to widespread thunderstorm development across the area by 18 UTC. These include:

- Moderate convective available potential energy (CAPE) values of 1000 J/Kg.
- Rapidly eroding convective inhibition (CIN).
- Flow aloft parallel to a surface moisture gradient and axis of high theta-e.

The final critical pieces of the puzzle for this flash flood setup are the characteristics of the vertical shear profile. Many past prolific extreme rainfall events are characterized by:

- Strong low-level flow along a frontal boundary, mesoscale boundary, or orographic feature
- Warm and moist low level air
- CAPE ~500-1000 J/Kg
- CIN <200 J/Kg
- Weak mid and upper level flow parallel to a boundary or orographic features (Maddox et al 1979).

As previously highlighted, the setup for the 8 September 2014 event featured a prolific warm, moist layer from the low to mid-levels of the atmosphere, as well as adequate CAPE and CIN per the 12 UTC and 00 UTC NWS Las Vegas observed soundings on 8 and 9 September 2014, respectively (Fig. 4). It is noted that while low level flow was particularly weak for this event, 850-700 hPa winds favored a west-southwest to southwest direction for this event, keeping flow mostly parallel to a pre-existing axis of high theta-e at the surface (Fig. 5). The hodographs (Fig. 6) from the aforementioned observed soundings were favorable for pulse storm types, given the weak shear values in the cloud bearing layer (Weisman and Klemp 1986). The resultant storm motion vector was northeast, parallel to the existing surface moisture boundary, indicating the potential for training thunderstorms and an increased flash flood threat as a result. Training thunderstorms developed by 18 UTC and exhibited mesoscale characteristics consistent with past extreme rainfall events. These will be discussed more in detail in section 2.2.

2.1.2 *Predecessor Rain Events*

Predecessor rain events (PRE's) were first defined by Cote (2007) to describe sub-synoptic scale regions of impactful heavy rainfall events in advance of tropical cyclones. This work, along with subsequent studies in the following years exclusively investigates landfalling tropical cyclones east of the Rocky Mountains. With the past several eastern Pacific hurricane seasons being above climatological averages, there has been an increase in exceptional rainfall events across portions of the Southwestern United States associated with tropical systems that track over or near the Baja Peninsula. Hurricane Norbert in September 2014 yielded two separate PRE's that produced exceptional rainfall across the Phoenix, Arizona metropolitan area on the morning of 8 September, and across Moapa Valley, Nevada on the afternoon of 8 September. Both events featured organized convection that yielded 139.95 mm (5.51 inches) and 152.4 mm (6 inches) of rainfall, respectively, in 24 hours, satisfying the criteria of over four inches defined by recent research.

In terms of locations for PREs, Galarneau et al. (2010) highlighted the following synoptic locations as most favorable for PRE's:

- The right-rear quadrant of a jet streak

- Ahead of a mid-level mean long-wave trough axis or upstream from a short-wave ridge
- Near a low-level baroclinic zone or front
- On the periphery of a tropical moisture plume
- Near a low-level surface boundary

The 8 September 2014 PRE event in Moapa Valley featured four of the five outlined features. A weak trough moving inland over northern California combined with a weak ridge of high pressure over eastern portions of the Southwest funneled moisture from the remnants of Hurricane Norbert northward into the region (Fig. 7), as illustrated by the surface-based theta-e ridge over the region (Fig. 5). A surface moisture boundary across the region was a focal point for convection across the Las Vegas County Warning Area (CWA) at the beginning of the event. Infrared satellite imagery (Fig. 7) and regional composite radar mosaic (Fig. 8) show thunderstorm activity across Moapa Valley associated with the PRE on the northeastern periphery of Norbert's remnants.

2.2 *Radar analysis*

Convection along the Interstate 15 corridor in southern Nevada is well sampled by the NWS Las Vegas WSR-88D radar, located roughly twenty miles south of Las Vegas on top of Nelson Peak. The radar location with respect to the Moapa Valley is illustrated in Figure 9. Though convective initiation occurred between 13 and 14 UTC 8 September 2014 across portions of San Bernardino, California and Mohave, Arizona Counties, a broken line of intense thunderstorms did not develop until 18 UTC along a synoptic moisture boundary oriented from northeast to southwest across the region, with the most intense rainfall producing storms originating over the Spring Mountains and Sheep Range of Clark County, Nevada.

Individual thunderstorms in this broken line featured quasi-stationary storm motions parallel to the line's orientation, increasing the probability of thunderstorms training over a particular point, thus increasing rainfall duration (Doswell et al. 1996). These types of systems are of particular interest for forecasters, due to the frequency of flash flood events associated with them (Chappell 1986). Thunderstorms across Clark County featured several other important processes that enhanced the flash flooding threat along the Interstate 15 corridor from Las Vegas proper through the Virgin River Gorge. First, several individual thunderstorms within the broken line featured a back-building component to them, as illustrated by Figure 10 from Schumacher and Johnson (2005). Figure 11a illustrates a cancellation of the overall forward propagation of the resultant cluster of thunderstorms due to the backward propagation of individual cells, leading to increased duration of heavy rainfall and exceptionally high rainfall totals (Fig. 11b) across the Moapa Valley (Chappell 1986; Doswell et al. 1996). Secondly, these thunderstorms featured "low-echo centroids" (LECs), a type of convective cell where most of the reflectivity is located within the warm portion of the cloud bearing layer, allowing for rainfall produced from collision-coalescence (Vitale and Ryan 2012). Though this phenomenon remains difficult to quantify, an analysis of cases by Vitale and Ryan indicated several consistent features found in LEC storms. These include: radar reflectivity $\leq$60 dBZ within a storm cell, a long-lived steady state reflectivity of 45-55 dBZ, and increasing reflectivity with decreasing height within a storm cell due to the physical properties of the collision-coalescence process. Davis (2001) found that excessive rainfall events produced from collision-coalescence processes typically require:

- a deep warm-cloud layer,
- weak and/or shallow updrafts,
- limited cloud layer wind shear, and
- high relative humidity through a deep layer.

Given the environmental setup discussed in Section 2.1, it was anticipated that thunderstorms across the Las Vegas County Warning Area (CWA) were going to be efficient rainfall producers on 8 September 2014. The storms of interest that produced flash flooding across the Moapa Valley developed southwest of the town of Moapa, east of the initial broken line of thunderstorms that developed over western Clark County. These storms in particular exhibited quasi-stationary back building characteristics outlined by Schumacher and Johnson (2005), with numerous LEC thunderstorms (Fig. 12a) training over the town and the major washes north of Interstate 15 for a 3 hour period. Cross-section analysis (Fig. 12b) of these storms revealed shallow updrafts with the highest reflectivities within the warm cloud layer, defined as the layer from the lifted condensation level (LCL) to the -10°C isotherm. It is within this layer of the cloud where collision-coalescence (warm rain) processes can occur, provided that all water remains in liquid phase (Vitale and Ryan 2012). The shallow nature of the updraft is one indication that storm relative vertical velocities were weak enough for collision-coalescence to effectively occur, along with the relatively thin CAPE profile from the NWS Las Vegas observed soundings on 8 September 2014 (Zipser and LeMone 1980). This is vital due to the fact that convection that relies on collision-coalescence to generate rainfall are typically more efficient at converting available cloud moisture to precipitation than the Bergeron process, which involves water in the ice phase (Lamb 2001). These environmental and storm relative features satisfy each of the criteria required for excessive rainfall events from collision-coalescence outlined by Davis (2001), resulting in major flash flooding across the Moapa area.

The flood threat continued in areas downstream, south of Interstate 15, as several major washes, the California, Meadow Valley, and Weiser flow from north to south across Interstate 15 into the Muddy River. The Muddy River then flows southward through the cities of Logandale and Overton before draining into Lake Mead. Given the extreme nature of the rainfall produced over these washes, the flash flooding threat transitioned to a river flooding threat and lasted through the overnight hours of 8 September 2014.

3. RAINFALL ESTIMATION

Rainfall data from numerous sources were obtained and analyzed for the period of heaviest rainfall on 8 September 2014. Rainfall data has been subdivided by its spatial coverage. For example, there is point data such as from a rain gauge, or gridded data such as from remotely sensed estimates (i.e., WSR-88D radar). This section elaborates on both of these different data types used in this analysis. Section 3.1 discusses point rainfall data from official and partner sources followed by gridded rainfall data in Section 3.2. Section 3.3 discusses a comparison of the measured and estimated rainfall data to rainfall frequencies for the Moapa Valley area.

3.1 *Point rainfall data*

Point rainfall data were obtained from official and partner agency sites, including Automated Surface Observing System (ASOS; automated stations that typically are located at airports), Hydrometeorological Automated Data System (HADS; automated stations that record weather and river data), United States Geological Survey (USGS; automated stations co-located with river observations), and Clark County Regional Flood Control District (CCRFCD; automated gauges owned, operated, and maintained by the District). All of these would typically be available in real-time to NWS forecasters. The locations of rain gauge sites and storm total rainfall for the Moapa Valley are shown in Figure 13. The rainfall recorded at the Weiser Wash CCRFCD gauge (118.11 mm or 4.65 inches) is the maximum amount of rainfall measured by point data.

3.2 *Gridded rainfall data*

The recently added dual-polarization (dual-pol) WSR-88D data provide the ability of forecasters to discriminate between spherical raindrops, elongated raindrops, and rainfall mixed with hail, which results in various precipitation rates and estimated accumulations for a given reflectivity. The biggest strength of these estimated accumulations is that they are available for warning forecasters within minutes of the radar detecting precipitation. Storm total rainfall from the dual-pol quantitative precipitation estimate (QPE) product is illustrated by Figure 14.

Another dual-pol radar-derived precipitation estimate available to forecasters in near real-time is Q3, produced by the National Severe Storms Laboratory's (NSSL's) Multi-Radar Multi-Sensor System (MRMS; Zhang et al. 2014). Q3 QPE is derived from multiple radars that have been seamlessly mosaicked. Q3 also compares radar reflectivity to short-term model data to determine the best radar-rainfall relationship. Storm total rainfall from the Q3 QPE Hybrid Digital Precipitation Rate product is illustrated by Figure 15, where an area outside the gauge network is estimated to have received 152.4+ mm (6+ inches) of rainfall.

The official NWS QPE product (Fig. 16), created by the NWS River Forecast Centers (RFCs) and obtained in geographical information system format from the NWS Advanced Hydrologic Prediction Service (AHPS) precipitation page (water.weather.gov/precip/), is referred to as the multi-sensor best-estimate rainfall. It is created by mosaicking gridded radar estimates from individual radar sites, bias correcting the grids with automated rain gauges, and then quality controlling those grids every hour. This too indicated a localized area of 101.6-152.4 mm (4-6 inches) of rain.

3.3 ***Rainfall frequency***

Rainfall estimates can be compared to rainfall frequency data to estimate the average recurrence interval (ARI) of a storm, such as the Moapa Valley flash flood event. The ARI is the average period of time between events of a given magnitude, when averaged over a very long period of time. The annual probability (AP) of a given event is expressed by the following equation:

$$AP = \frac{1}{ARI}$$

A higher ARI, or lower annual percent chance, would imply a less frequent and perhaps more significant event. ARI rainfall estimates are available from NOAA Atlas 14 (Bonnin et al. 2011), produced by the NWS Hydrologic Design Studies Center (HDSC). The HDSC computes ARI rainfall estimates for storms with durations ranging from 5 minutes to 60 days. Of these storm durations, the 15-minute and 3-hour durations will be discussed in this section.

The entire rainfall event lasted less than 4 hours across the Moapa Valley area, with almost all rainfall occurring over a 3-hour period. The maximum 3-hour rainfall accumulations were compared to the ARI for each rain gauge in Moapa Valley located north of Interstate 15. The Mormon Mesa 1 rain accumulations, visible in Figure 13, depicted at least a 50 year ARI (2.0% AP) with this event. Meadow Valley Wash and Moapa gauges recorded at least a 200 year ARI (0.5% AP). California Wash 2 recorded at least a 500 year ARI (0.2% AP). Finally, Weiser Wash recorded at least a 1000 year ARI (0.1% AP) for this event, outlined in red in Figure 17. During one 15-minute increment, the Weiser Wash recorded 30.48 mm (1.2 inches; Fig. 18), which is at least a 200 year ARI (0.5% AP) for that 15 minute time period, outlined in green in Figure 17. The dual-pol radar and Q3 storm total QPE values, where no rain gauges were present, also implied a greater than 1000 year ARI (0.1% AP) for this event. These ARI values clearly demonstrate the rainfall accumulations are extreme for this particular area.

Another way of investigating the rainfall frequency of this event is by looking at the average rainfall accumulation this area experiences annually (Fig. 19). Moapa Valley typically experiences between 101.85 and 152.4 mm (4.01 and 6 inches) of precipitation annually. The Weiser Wash total rainfall accumulation as well as the dual-pol radar and Q3 storm total QPE illustrate portions of Moapa Valley received their average annual precipitation within a 3-hour time period during this event.

4. NWS LAS VEGAS PRODUCTS AND SERVICES

The first mention of potential impacts from Hurricane Norbert came as early as 31 August 2014 in NWS Las Vegas area forecast discussions. As confidence increased over the next several days in the setup being favorable to induce a gulf surge (Higgins and Shi 2005), decision support services (DSS) increased with the initialization of email briefings to core partners (Fig. 20) and dissemination of social media graphics to the public (Fig. 21) on 3 September 2014. These forms of DSS highlighted the potential threats associated with moisture from Norbert, as well as the forecast confidence five days before the event (Mullins et al. 2012). These services continued through the morning of the event. A conference call was organized and hosted by NWS Las Vegas on 5 September 2014 to brief local, state, and federal partners, including media, on the latest forecast details and confidence, as well as to coordinate the planning and messaging efforts ahead of the event. The decision to issue a flash flood watch for much of the forecast area, including Clark County, from Sunday, 7 September through Monday, 8 September 2014 was made by NWS Las Vegas and conference call participants were briefed in full on the details. Clark County Emergency Management followed by initiating a web-based emergency operations center (WebEOC; Fig. 22) event page to allow information sharing between NWS Las Vegas and organizations associated with event preparation and response.

NWS Las Vegas DSS transitioned from forecasting and planning to dissemination of short-fused information, active weather warnings and eventually on-site support on 9 September 2014. WebEOC posts continued for major updates to partners throughout the day and NWS Las Vegas social media presence increased through the use of frequent “situation reports” (Fig. 23), designed to give the public the latest weather and warning information. The initial flash flood warning for the Moapa Valley and Interstate 15 was issued at 1:17 PM PDT. Between 2:30-2:40 PM PDT, NWS Las Vegas received reports of a possible dam failure and swift water rescues occurring along Interstate 15. Based on this information and rain gauge data from the CCRFCD, the flash flood warning was upgraded to a flash flood emergency. As thunderstorms began to diminish and the severity of the situation was realized, a portion of NWS Las Vegas operations shifted to response mode, covering numerous local and national media interviews, participating in several county EOC conference calls and activating the office Weather Deployment Team. The Deployment Team was developed at NWS Las Vegas to provide increased on-site weather support for core partners during planned, large venue events and high impact weather events. Staffing was modified accordingly to allow for multiple deployments to the Clark County EOC through the day on 9 September 2014 to provide weather support for the response in Moapa Valley. The initial deployment took place at 2:30 AM PDT on 9 September, with shift changes at 9:00 AM and 3:00 PM PDT before transitioning back to remote support at 7:00 PM PDT. Email briefings and posts to WebEOC continued through 22 September 2014 to assist with cleanup operations and the threat of another tropical system in the Eastern Pacific, Odile.

After action reviews were conducted after the event to determine the quality and effectiveness of NWS Las Vegas products and services. Of our products and services, our email briefings were the most useful tool for our partners. The concise detail of the potential threats and indications of confidence in the forecast allows our partners to plan with confidence ahead of weather events, leading to better, more timely response during big events like the Moapa Valley flash flood. According to Clark County Emergency Management, the presence of the Weather Deployment Team was one of the “most influential services” we provided during the event aftermath. This service increased the trust between the responding agencies and the NWS, helping enhance response efforts in the Moapa Valley.

5. IMPACTS

Extreme rainfall has an enormous impact on all facets of transportation (WIST 2005). Two important societal impacts arising from heavy rain that affect all modes of transportation include loss of visibility and flash flooding. Both phenomena occur on small time scales and have the potential to be deadly. On roadways, reduced visibility can yield an increase in accidents (WIST 2002). Railway and aviation transportation typically experience delays during heavy rain events due to the mitigating responses to reduced visibility. Flash flooding poses a more serious threat to both roadway and railroad operations, due to the increased likelihood of road and rail washouts, damage to sensors, switches, and signals, as well as the potential for mudslides and high water over roads and tracks (WIST 2002). Impacts to transportation had the most profound effect during the Moapa Valley flash flood, due to damaged infrastructure severely limiting major arterial connections through the area. These effects will be discussed more in depth in this section.

According to the National Oceanic and Atmospheric Administration (NOAA 2006), flooding costs an average of over two billion USD in damages every year. The flood event of 8 September 2014 in the Moapa Valley totaled over nine million USD in damages. The largest impacts of the event were transportation based, with over five million USD alone for roadway and railroad repairs (Storm Data, accessed 2014). The most costly impact was Interstate 15 getting washed out in many sections along a 20 mile stretch through the Moapa Valley (Figs. 24 and 25) and extending to the Arizona state line. This effectively cut off the area for several days and affected traffic flow for an extended period of time due to repair efforts; thus affecting area businesses and severely compromising infrastructure. Long haul trucking and transportation services as well as other travelers were relegated to a detour along two lane Nevada and Utah state highways between Las Vegas and St. George that added eight to ten hours to the commute due to the heavy volume of traffic (Fig. 26). While businesses in small towns along the detour route flourished, businesses in Moapa Valley suffered as a result of the road closures. Trucking companies lost money taking the 77 mile detour, due to lost time for their freight and additional fuel costs. Federal regulations restrict truckers from driving more than 11 hours a day, with a mandatory 10 hour rest period following a full shift. Therefore, some trucking companies resorted to using two drivers to complete the detour, doubling labor costs and pushing total additional costs upward to over ten million USD (Las Vegas Review-Journal 2014). One lane of the interstate was re-opened in each direction by 12 September 2014 for non-commercial vehicles, with long haul restrictions remaining in effect for trucking and transportation services through 18 September (Las Vegas Review-Journal 2014). Repairs to Interstate 15 took several months to complete, with vast improvements made to drainage along the route. Union Pacific Railroad experienced a track washout near Moapa, in the Caliente Subdivision which connects Los Angeles to Salt Lake City (Fig. 27). Repairs to the track took two days to complete, with services resuming late on 11 September 2014. Shipments experienced an average delay of 48 to 72 hours due to backlogged traffic (Union Pacific 2014).

Of the total damages to infrastructure from this event in Clark County, approximately 66 percent of damage occurred in the Moapa Valley, prompting the Clark County

Commission and Governor's Office to declare a state of emergency for the area. In all, approximately 140 homes received flood damage in the Moapa Valley, with more than 190 people displaced to shelters at area schools. Power to the valley was disrupted through the afternoon and evening of 8 September, as Reid Gardner Generating Station was inundated with up to 1.22 meters (four feet) of water in their substations and less than a meter (several feet) in the power plant itself. Power service was resumed during the early morning hours of 9 September from the backup station in Overton, NV, which supplied power to the area while a two week cleanup effort at the main station took place. In all, cleanup and repairs continued for several months in Moapa Valley, with the infrastructure slowly returning to normal in the area.

6. CONCLUSIONS

Tropical moisture associated with the remnants of Hurricane Norbert in the Eastern Pacific Ocean and Tropical Storm Dolly in the Gulf of Mexico caused a surge of anomalous moisture into the Southwest United States. Significant impacts from tremendous rainfall occurred on 8 September 2014 across Moapa Valley. Rainfall amounts up to 118.11 mm (4.65 inches) were measured from CCRFCD automatic rain gauges. The NWS WSR-88D estimated rainfall totals in excess of 152.4 mm (6 inches) for some locations outside of the rain gauge network. Substantial runoff from this rainfall flowed generally from north to south through the Meadow Valley Wash, Weiser Wash, and Muddy River, inundating and exceeding the capacity of the Interstate 15 drainage system. There were major damages to Interstate 15, which caused both north- and south-bound lanes to be closed for several days, with long detours put in place. The damage to Interstate 15 cost $5 million USD to repair, while additional Clark County infrastructure and residential damages totaled nearly $1 million USD. Including Moapa Valley local business revenue lost due to diverted traffic, long-haul trucking revenue lost due to the longer detour commute, repair and cleanup of private company infrastructure, and the total in damages increases to over $9 million USD.

NWS Las Vegas email briefings to core partners and a flash flood watch were issued days before the actual event, discussing increased confidence of flash flood potential across the region. Flash flood warnings for Moapa Valley were issued well in advance of the first reports of flooding. Heightened wording, such as flash flood emergency, was used to increase awareness of the most severe flash flood impacts. NWS Las Vegas conducted conference calls with Clark County Emergency Management and provided on-site support at the County EOC for 16.5 straight hours, utilizing three shifts. When NWS Las Vegas transitioned back to remote support, the email briefings and posts to WebEOC continued through 22 September 2014 to assist with cleanup operations and the potential for other weather threats.

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8. FIGURES

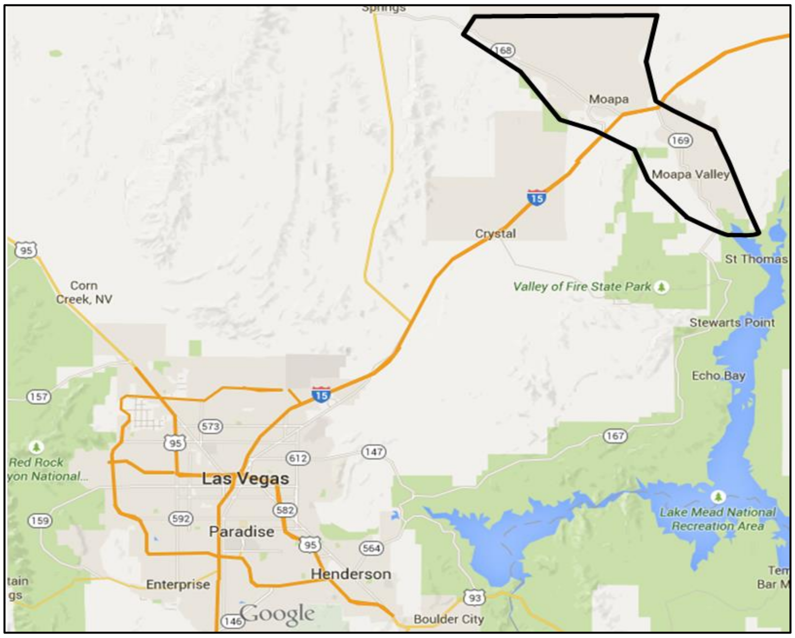

Figure 1. Moapa Valley, Nevada, outlined in black, is approximately 72.4 km (45 miles) northeast of Las Vegas, as illustrated by Google Maps.

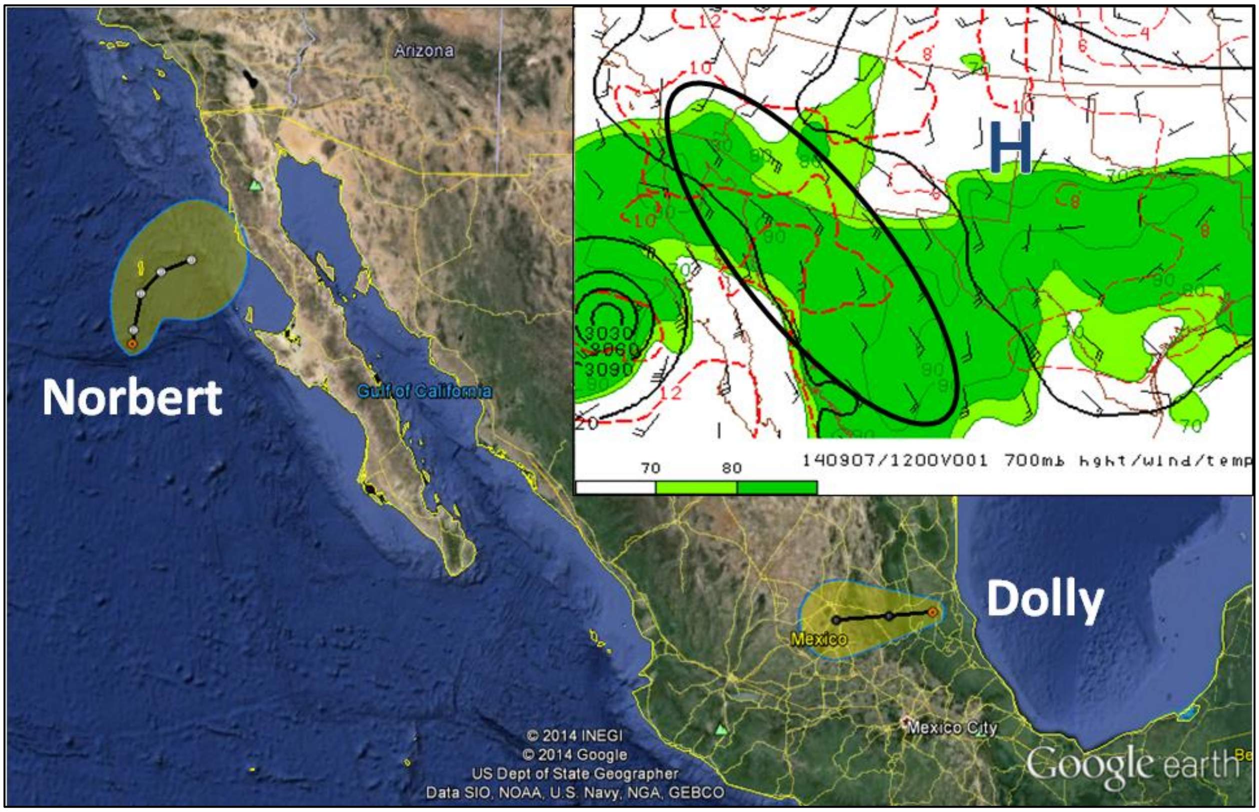

Figure 2. Moisture sources associated with the 8 September 2014 Moapa Valley flash flood. As discussed in Section 2.1.1, Hurricane Norbert and Tropical Storm Dolly contributed to the anomalous amounts of moisture across the region ahead of an approaching upper level shortwave.

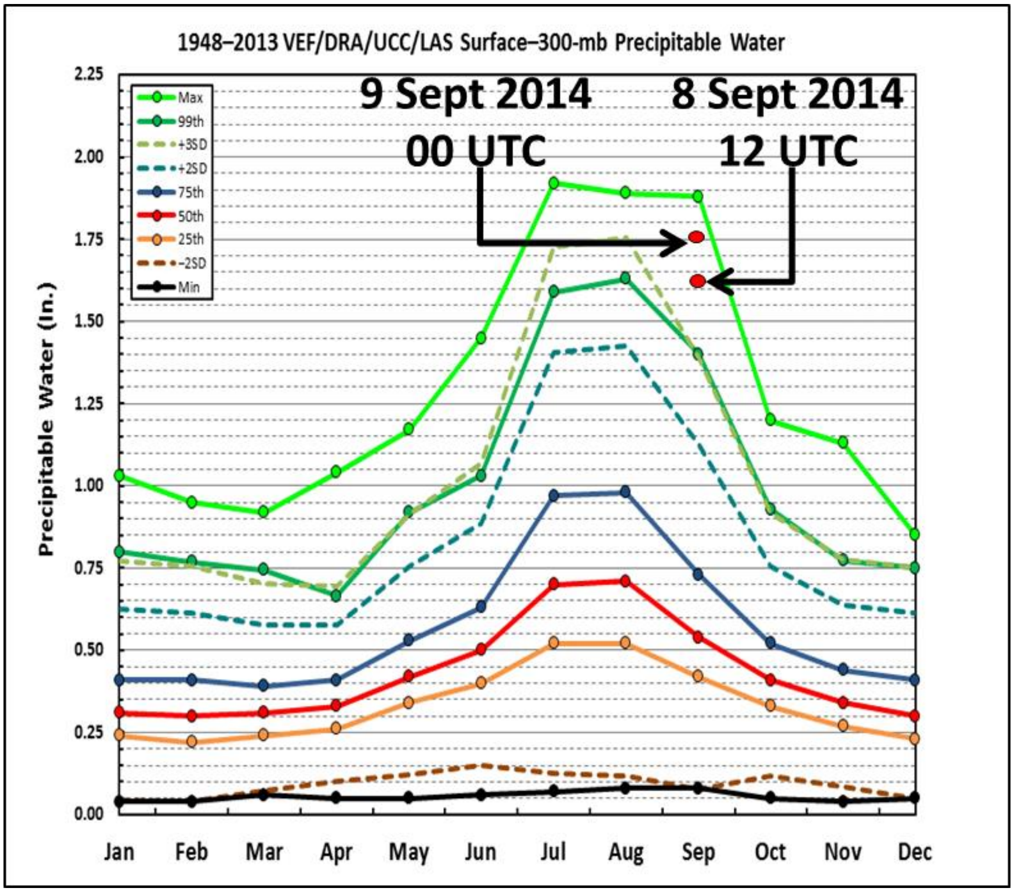

Figure 3. Precipitable Water climatology for the Las Vegas (LAS) sounding location at NWS Las Vegas. The 12 and 00 UTC observed soundings on 8 and 9 September 2014 measured 41.15 mm (1.62 inches) and 44.20 (1.74 inches) of precipitable water (noted as the red dots), which are greater than 3 standard deviation above normal for early September. While daily records were broken for 12 UTC on 8 September and 00 UTC on 9 September 2014, the event failed to match the record set for the month of September, denoted by the green “max” line.

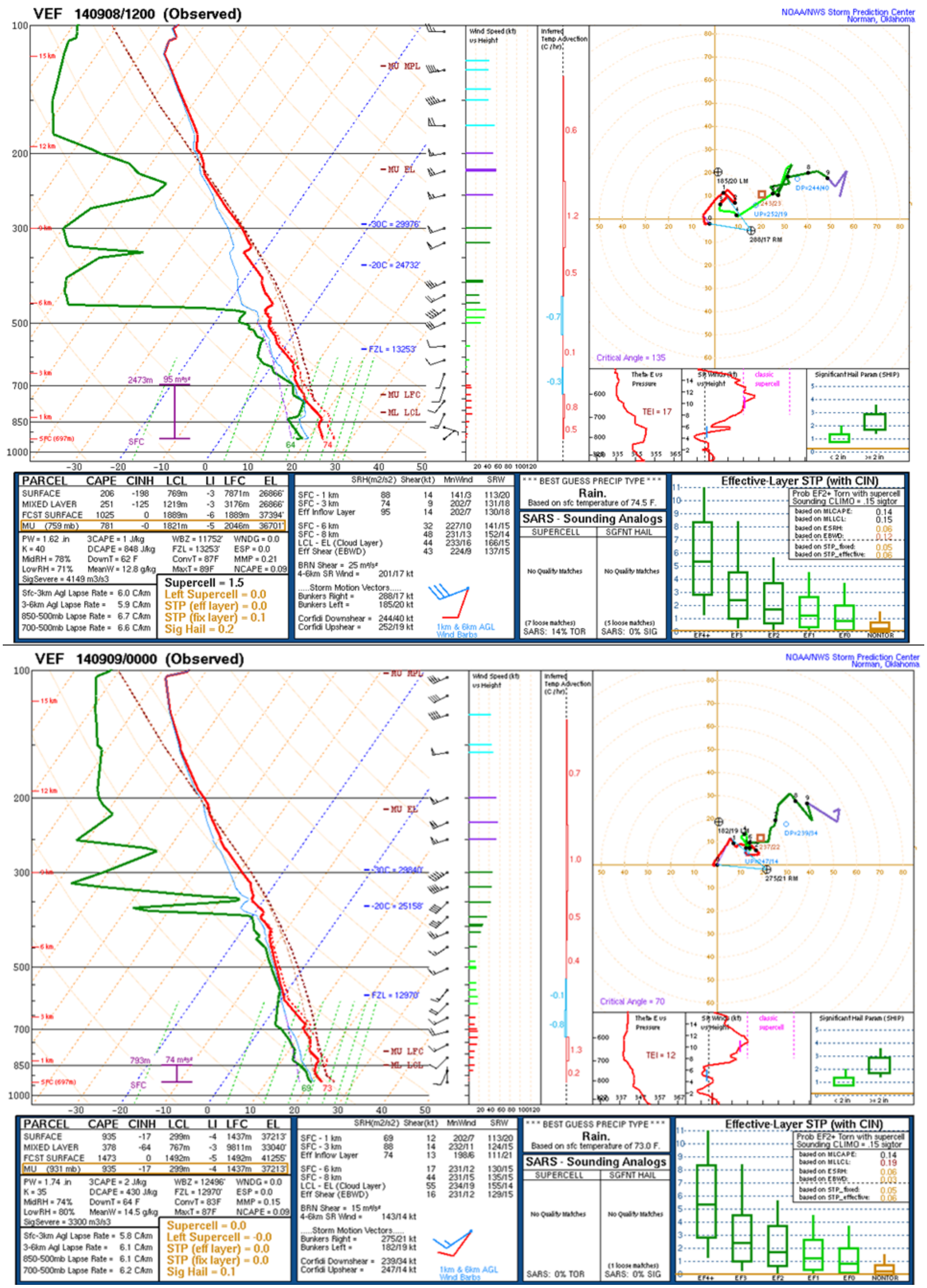

Figure 4. The 12 UTC 8 September (top) and 00 UTC 9 September (bottom) observed soundings from NWS Las Vegas. Note the parameters consistent with past prolific rainfall events in the two soundings, outlined by Maddox et al. (1979) and discussed more in detail in Section 2.1.1.

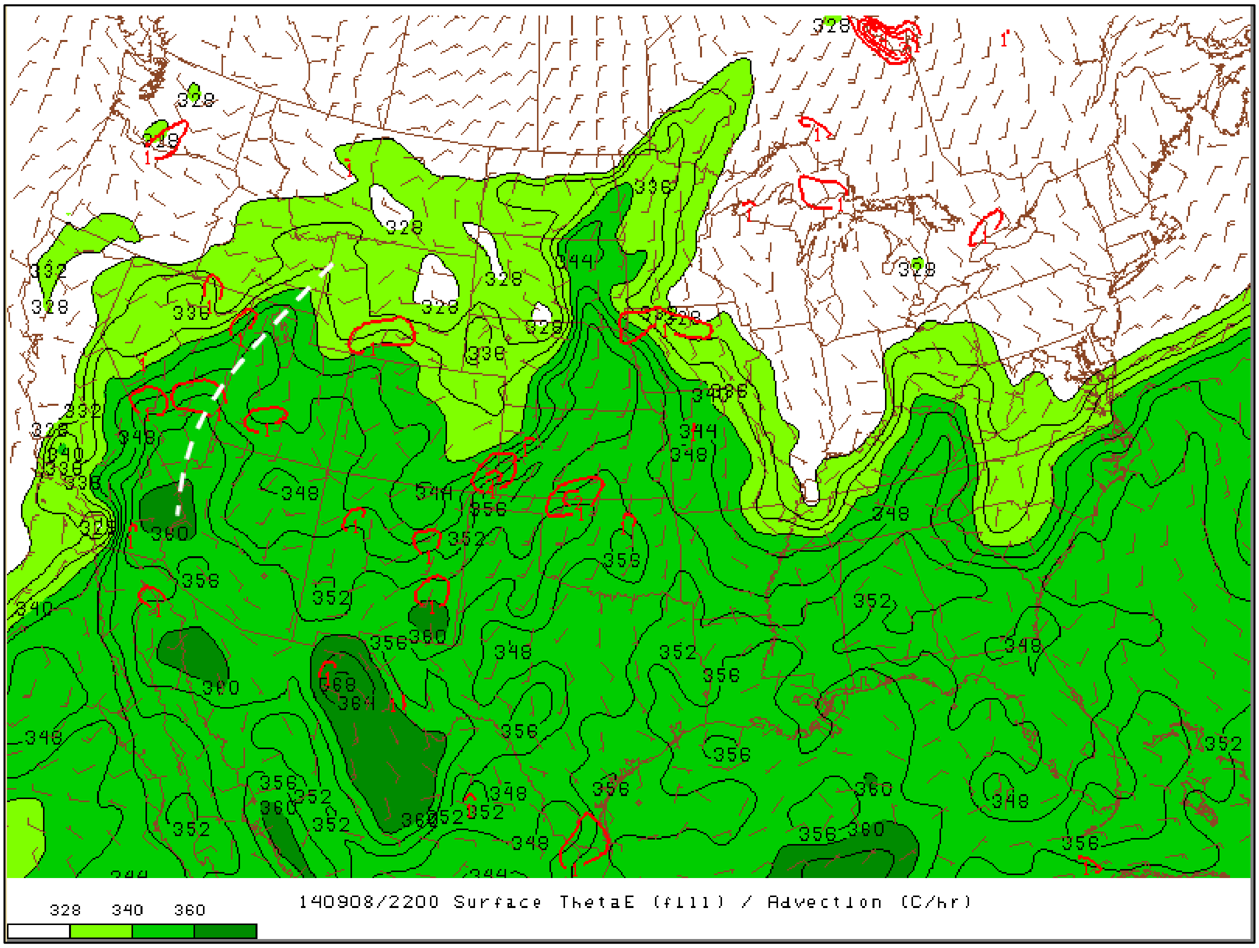

Figure 5. Surface theta-e chart at the time of intense rainfall across Moapa Valley, Nevada. Note the ridge axis (dashed white line) running through portions of eastern Clark County, NV. This is a favored location for PRE's as defined by Galarneau et al. (2010). This is discussed in detail in Section 2.1.2.

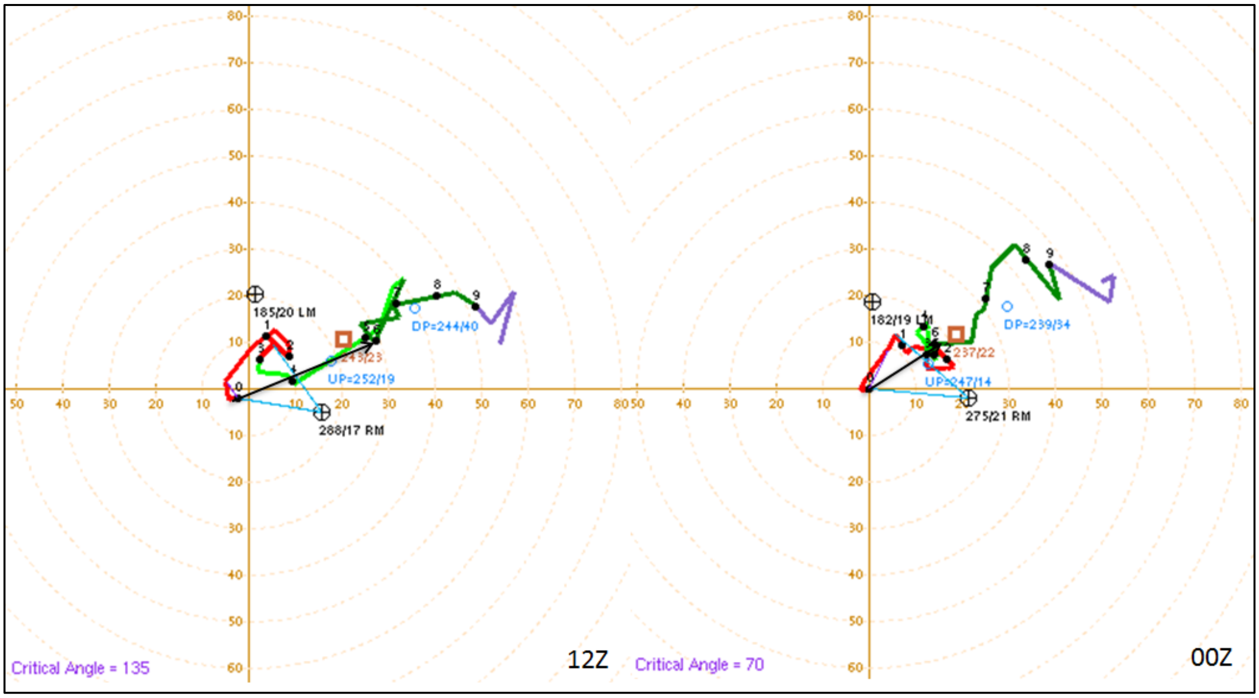

Figure 6. The hodographs associated with the 12 UTC 8 September (left) and 00 UTC 9 September (right) 2014 observed soundings from NWS Las Vegas. These shear profiles are consistent with Weisman and Klemp (1986) in indicating pulse like convection. The resultant storm motion vector is indicated in black in each hodograph.

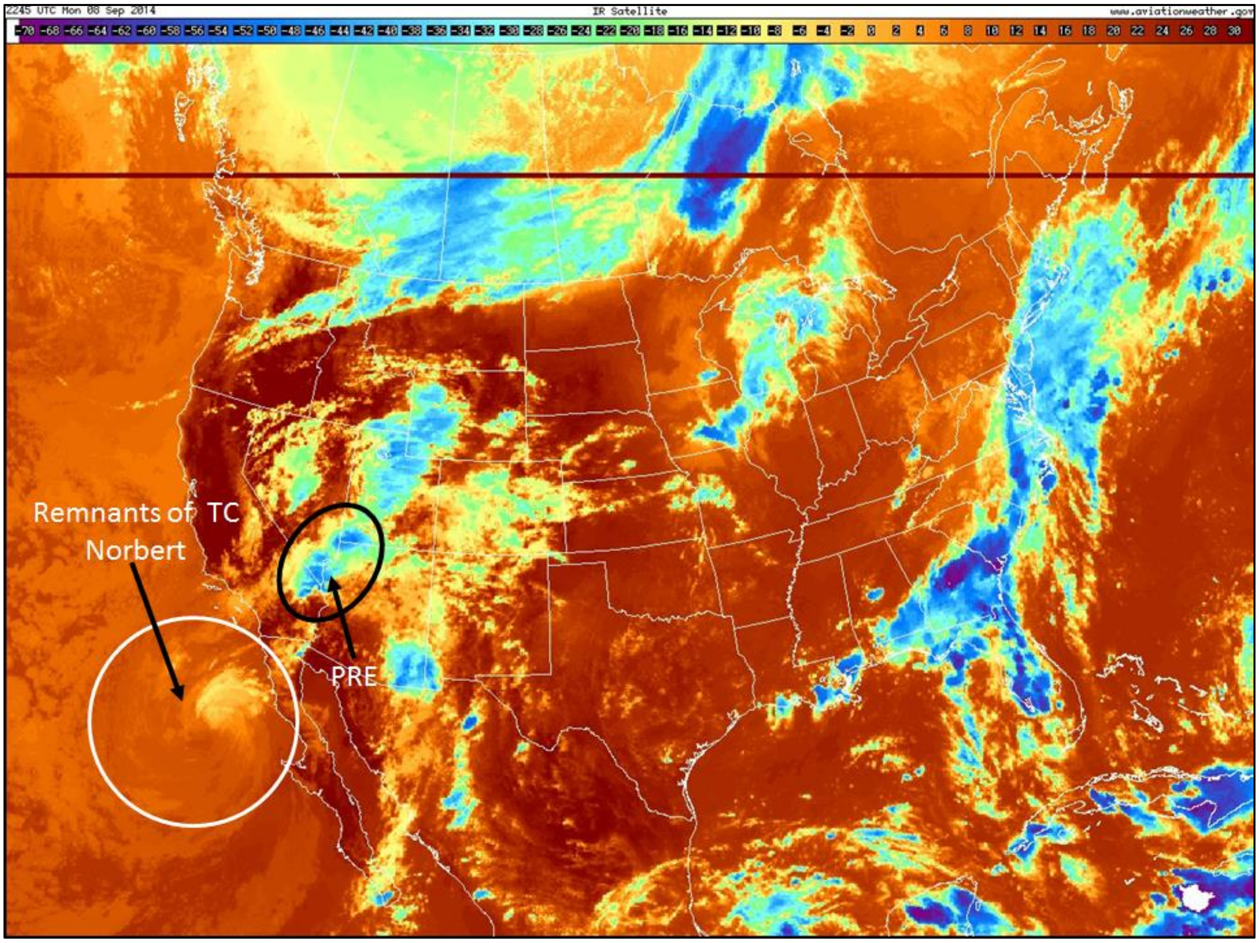

Figure 7. Color Enhanced Infrared Satellite depicting the location of the remnant circulation of former Hurricane Norbert with respect to the resultant convection across portions of the Desert Southwest on 8 September 2014. Image time, 2245 UTC, was in conjunction with heavy thunderstorms over Moapa Valley, Nevada.

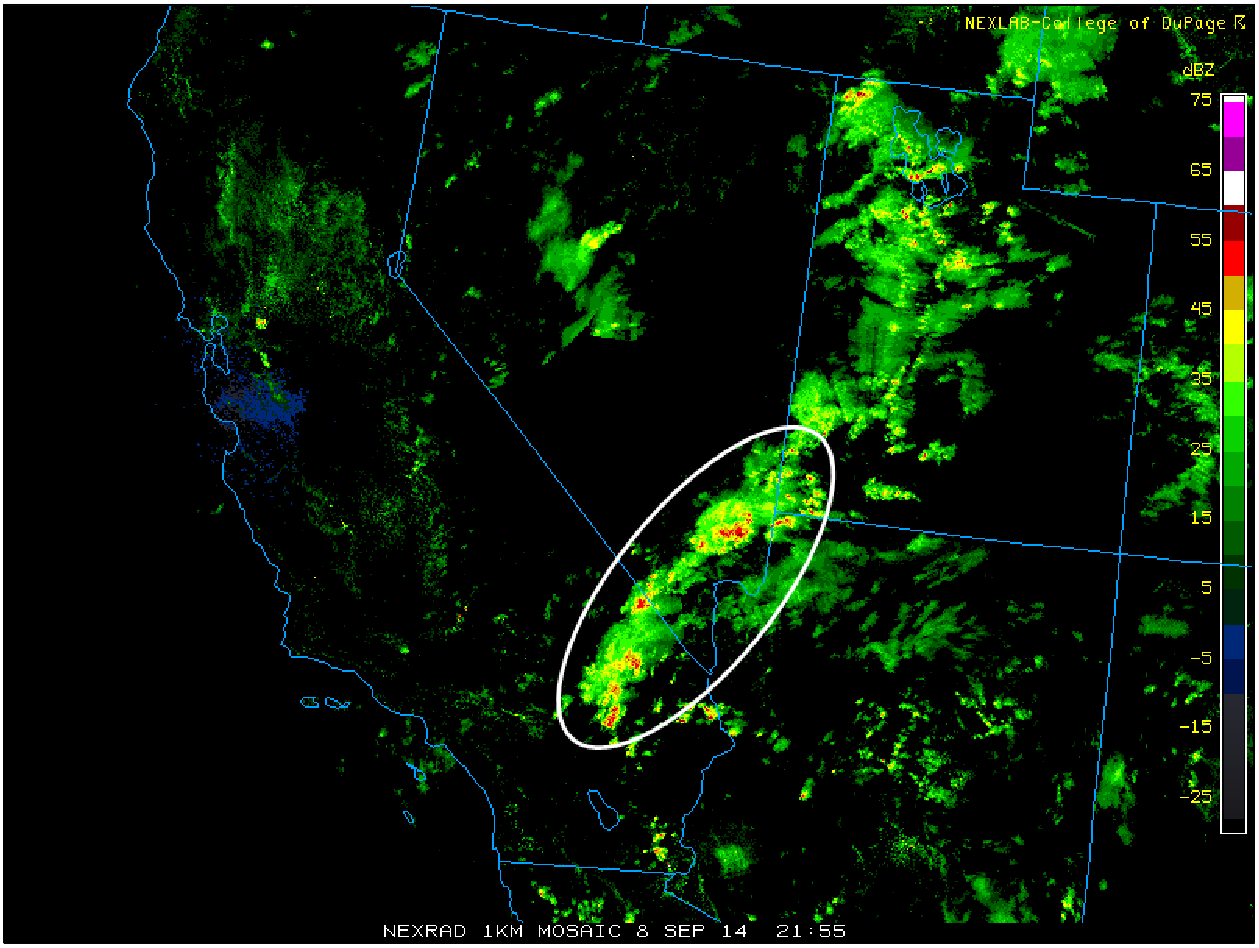

Figure 8. Regional composite radar mosaic at 2155 UTC showing a broken line of thunderstorms across southern Nevada along the surface moisture gradient.

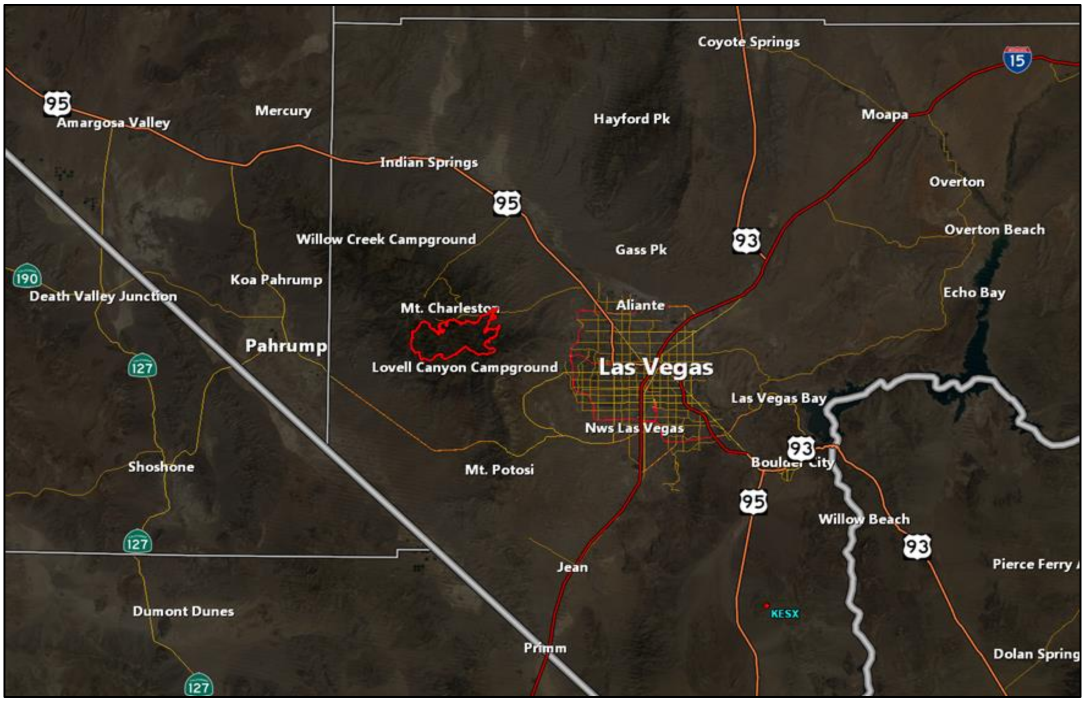

Figure 9. The Las Vegas WSR-88D Radar (KESX) is located approximately 111.05 km (69 miles) southwest of the Moapa Valley, as illustrated by Gibson Ridge Software. *Disclaimer: Reference to any commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its recommendation or favoring by the United States Government or NOAA/National Weather Service. Use of information from this publication shall not be used for advertising or product endorsement purposes.*

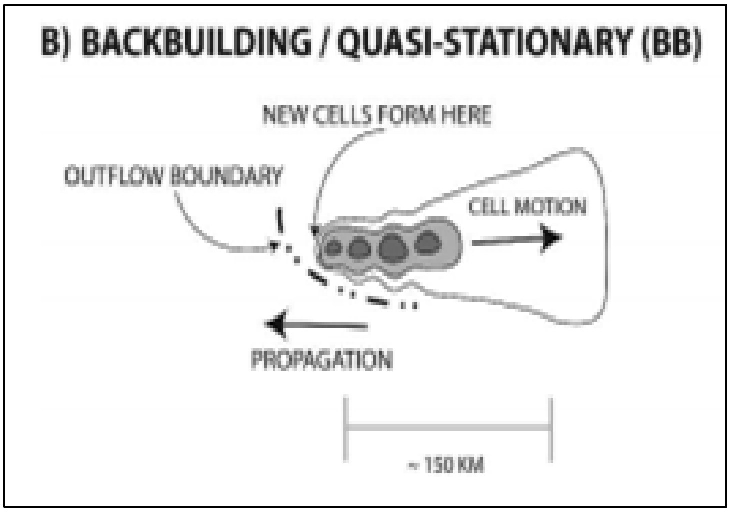

Figure 10. Adopted from Schumacher and Johnson 2005. This figure illustrates the back-building patterns of extreme rain producing mesoscale convective systems (MCSs). Though the Moapa Valley case did not involve an MCS, individual thunderstorms exhibited these characteristics, leading to training thunderstorms over Moapa and surrounding major washes, resulting in significant flooding across the area.

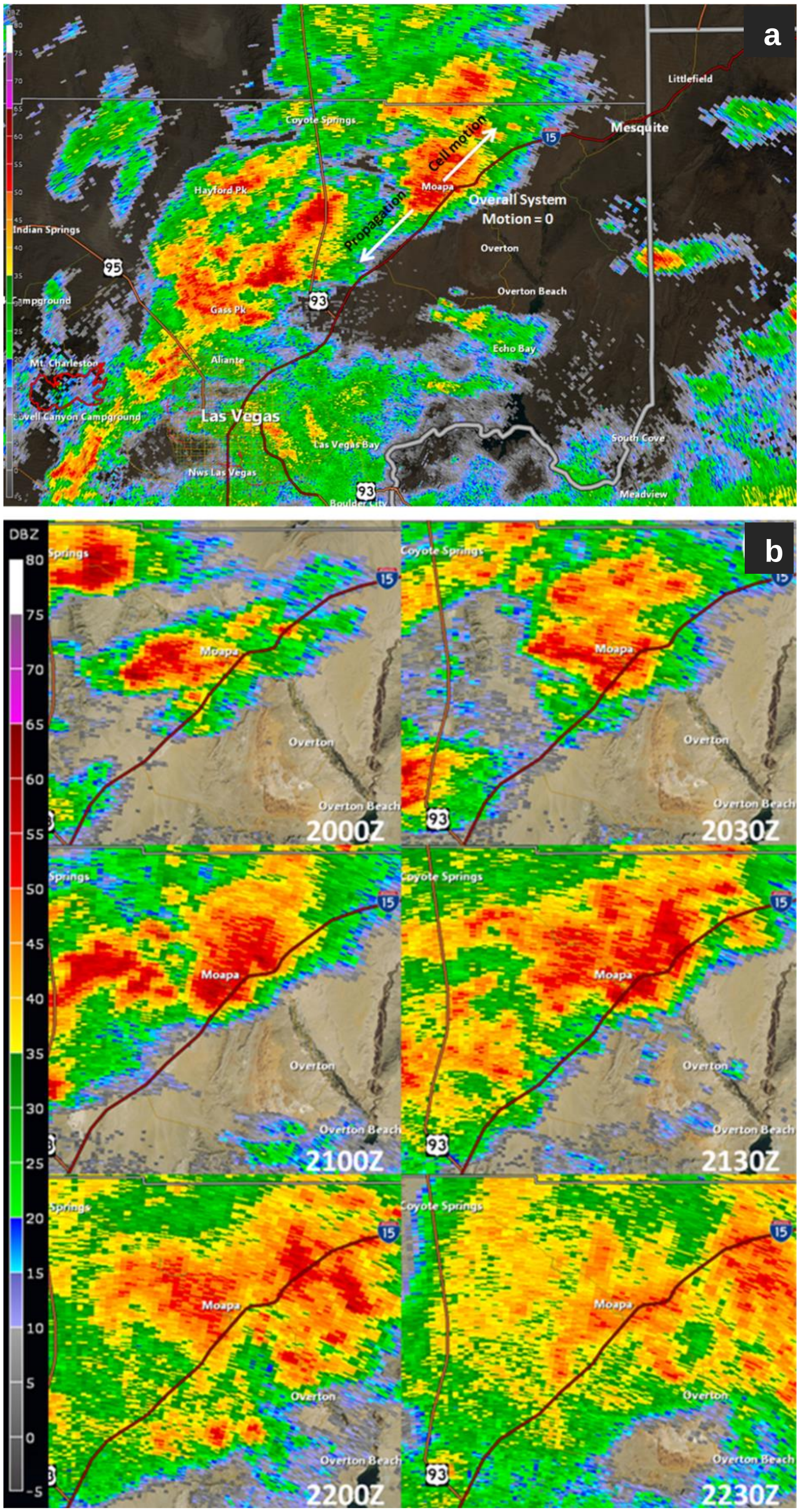

Figure 11. (a) Illustrates the cancellation of the forward propagation of the thunderstorm cluster over Moapa, due to the backward propagation of individual storm cells to the southwest. This led to training thunderstorms over the area, yielding a near three hour duration of extreme rainfall over the region, illustrated by (b). Convection along the surface moisture gradient to the west eventually merged with these cells, causing the entire system to propagate eastward.

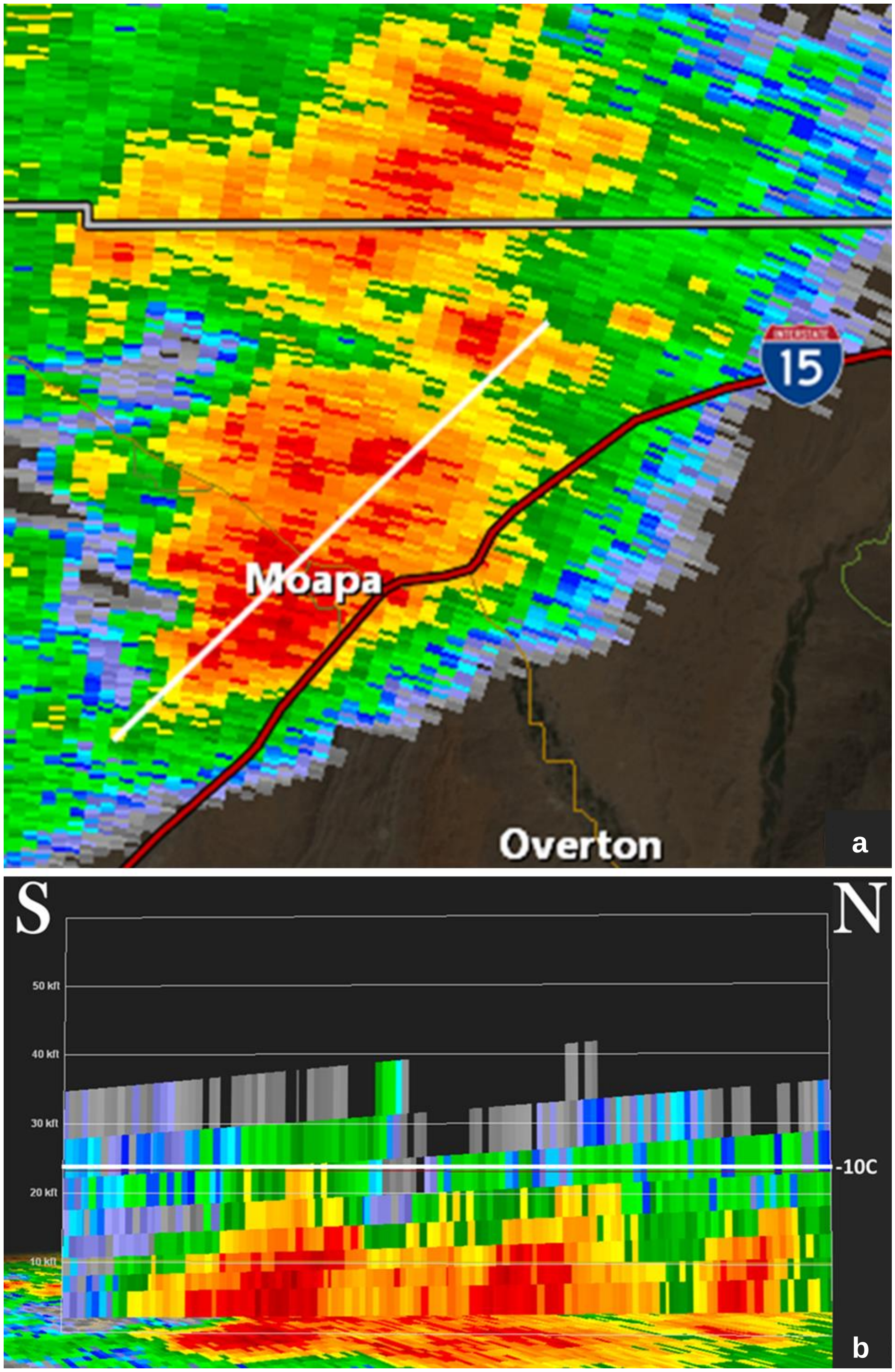

Figure 12. (a) KESX WSR-88D reflectivity at 2047 UTC 8 September 2014. The white line through the storm indicates the orientation of the cross section shown in (b). Note the bottom heavy nature of each of the thunderstorm cores, as well as the limited extent of the updrafts, with each core remaining below the -10°C isotherm. This is discussed more in-depth in Section 2.2.

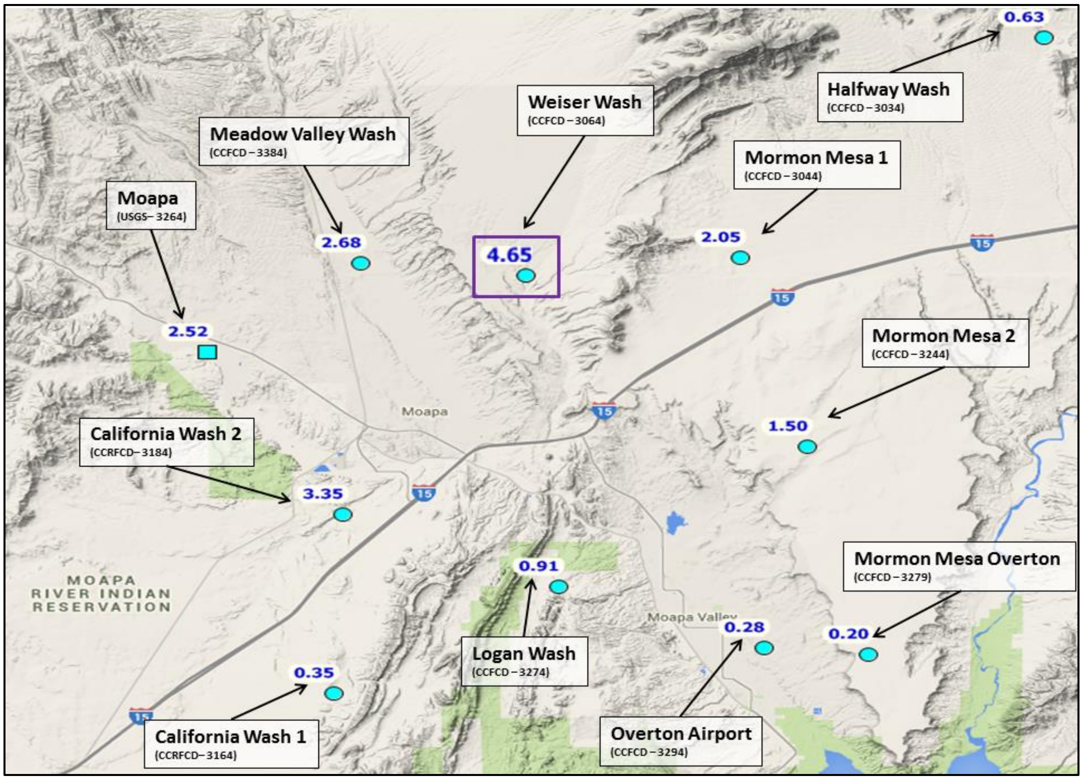

Figure 13. Locations of rain gauge sites and storm total rainfall across Moapa Valley. Weiser Wash, outlined with a purple square, measured the greatest rainfall accumulation (118.11 mm or 4.65 inches).

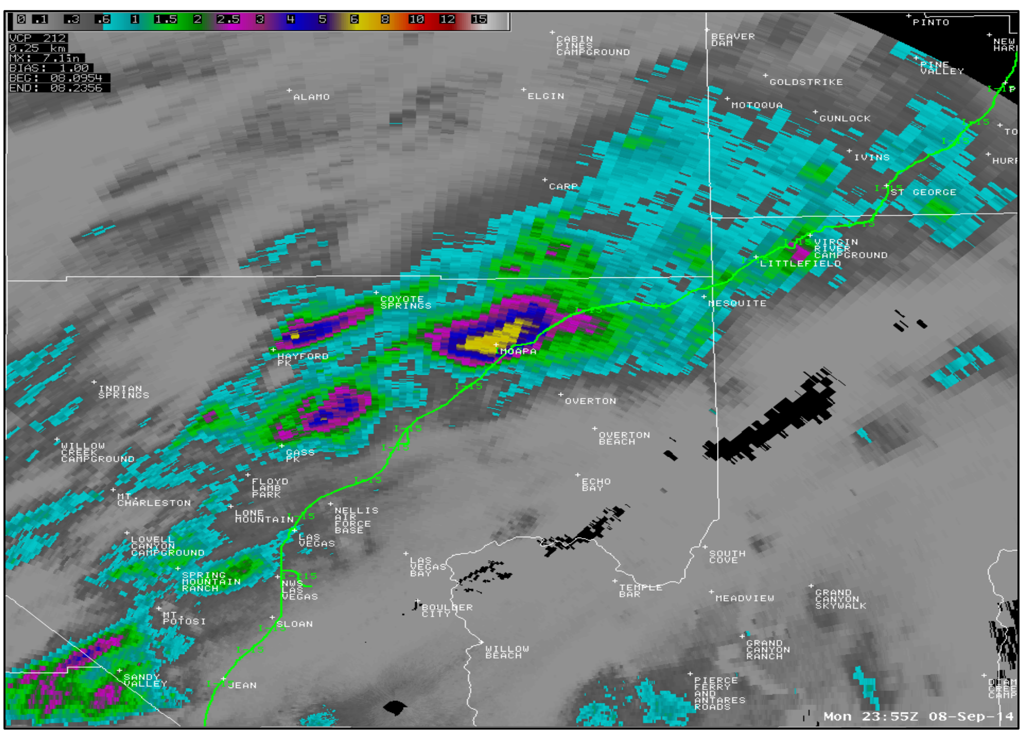

Figure 14. Storm total rainfall from the dual-pol quantitative precipitation estimate (QPE) product illustrates a localized area of 152.4 mm (6 inches) of rain fell just north of Interstate 15 across Moapa Valley.

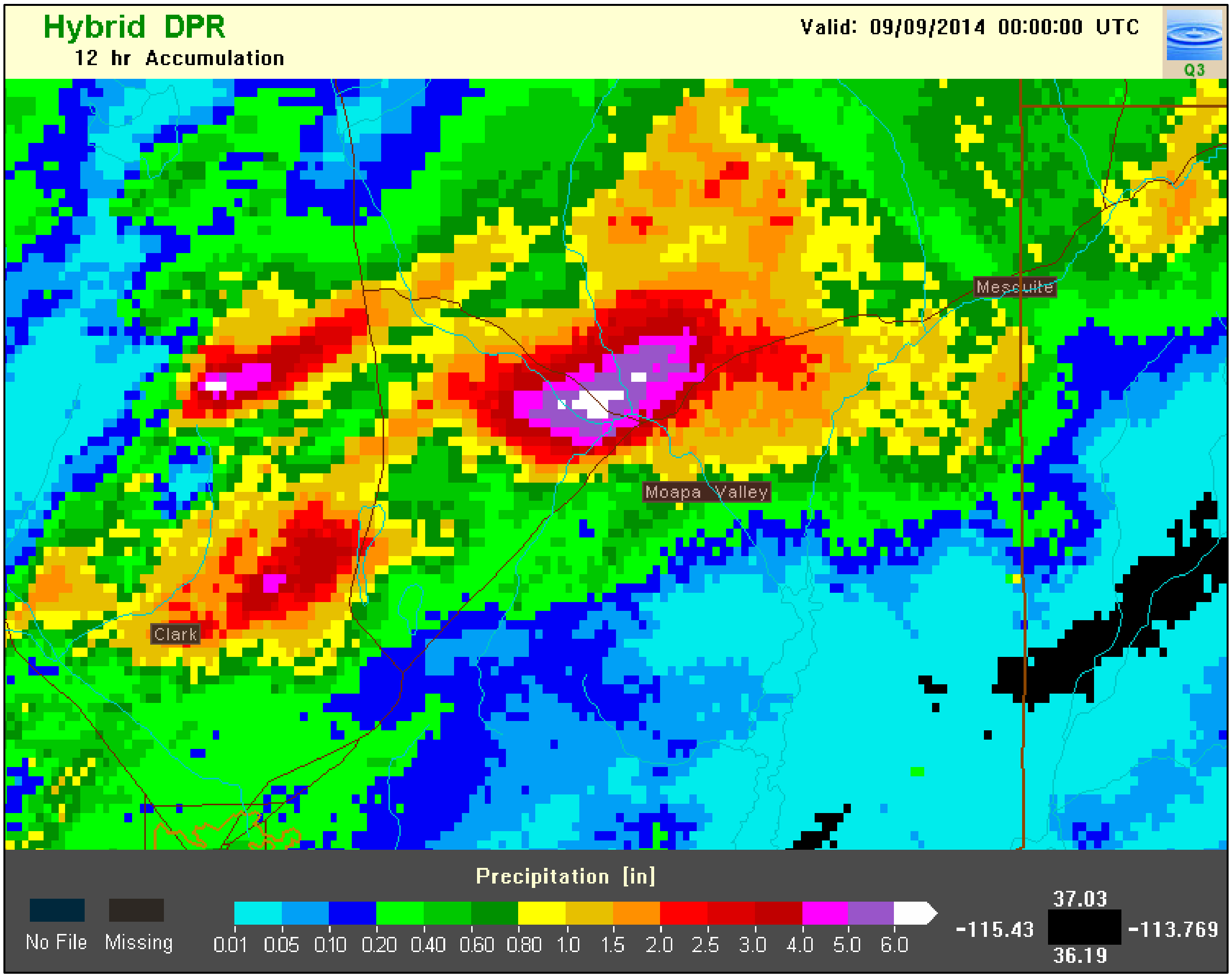

Figure 15. Storm total rainfall from the mosaicked dual-pol Q3 QPE (Hybrid Digital Precipitation Rate) product illustrates a localized area of 152.4 mm (6 inches) of rain fell just north of Interstate 15 across Moapa Valley, similar to Figure 14.

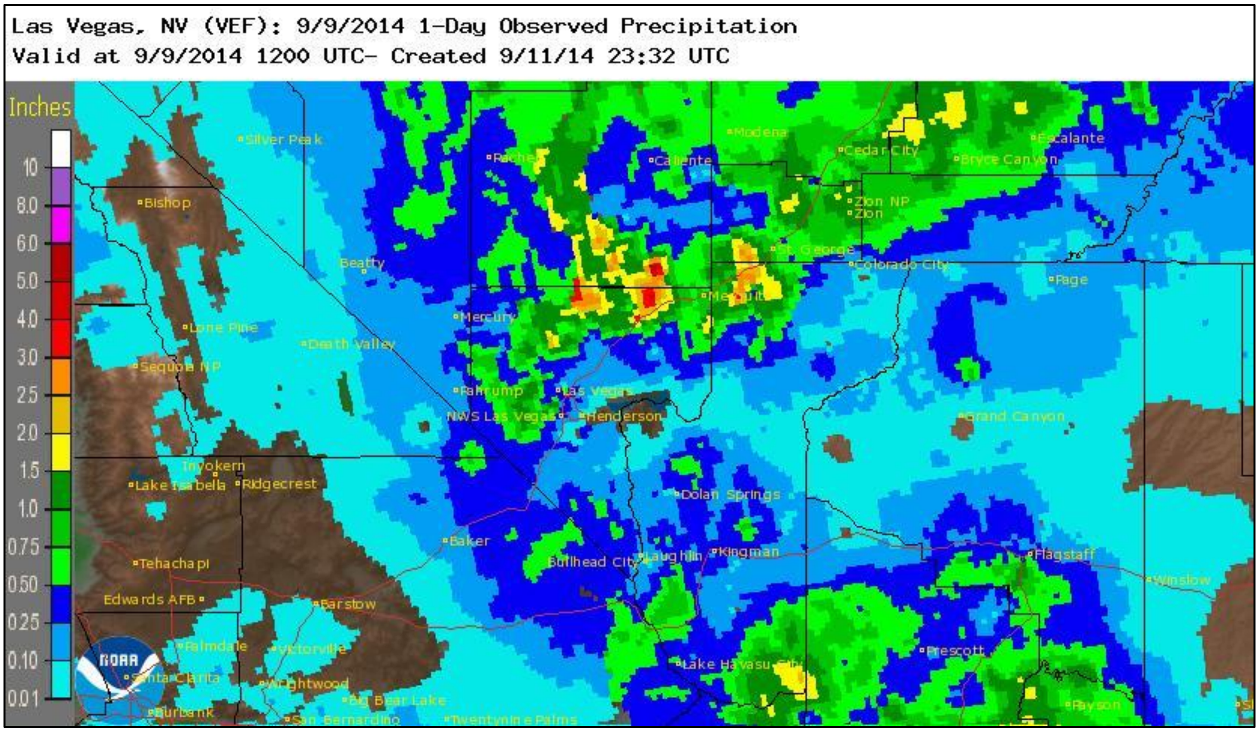

Figure 16. The official NWS mosaicked QPE product created by the NWS River Forecast Centers (RFCs), which depicts a localized area of 101.6-152.4 mm (4-6 inches) of rainfall within the same location as shown in Figures 14 and 15.

PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]										
Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.124 (0.103-0.149)	0.162 (0.136-0.198)	0.230 (0.190-0.279)	0.286 (0.235-0.346)	0.366 (0.297-0.445)	0.434 (0.349-0.529)	0.510 (0.403-0.625)	0.594 (0.459-0.734)	0.721 (0.544-0.904)	0.828 (0.611-1.05)
10-min	0.189 (0.157-0.227)	0.247 (0.207-0.301)	0.349 (0.288-0.424)	0.434 (0.357-0.526)	0.557 (0.453-0.678)	0.660 (0.531-0.804)	0.776 (0.613-0.951)	0.904 (0.698-1.12)	1.10 (0.827-1.38)	1.26 (0.930-1.60)
15-min	0.234 (0.194-0.282)	0.307 (0.256-0.373)	0.433 (0.358-0.525)	0.538 (0.443-0.652)	0.690 (0.561-0.840)	0.818 (0.658-0.998)	0.962 (0.760-1.18)	1.12 (0.866-1.39)	1.36 (1.02-1.71)	1.56 (1.15-1.99)
30-min	0.316 (0.262-0.380)	0.413 (0.345-0.503)	0.583 (0.482-0.707)	0.725 (0.596-0.878)	0.930 (0.755-1.13)	1.10 (0.887-1.34)	1.30 (1.02-1.59)	1.51 (1.17-1.86)	1.83 (1.38-2.30)	2.10 (1.55-2.68)
60-min	0.391 (0.324-0.470)	0.511 (0.427-0.622)	0.721 (0.596-0.876)	0.897 (0.738-1.09)	1.15 (0.935-1.40)	1.36 (1.10-1.66)	1.60 (1.27-1.96)	1.87 (1.44-2.31)	2.27 (1.71-2.84)	2.60 (1.92-3.32)
2-hr	0.472 (0.395-0.564)	0.606 (0.511-0.730)	0.827 (0.691-0.999)	1.01 (0.839-1.22)	1.29 (1.05-1.55)	1.51 (1.22-1.82)	1.77 (1.41-2.13)	2.05 (1.59-2.49)	2.47 (1.87-3.03)	2.83 (2.08-3.50)
3-hr	0.534 (0.452-0.635)	0.683 (0.578-0.818)	0.921 (0.774-1.10)	1.11 (0.933-1.33)	1.38 (1.14-1.65)	1.61 (1.31-1.93)	1.85 (1.49-2.23)	2.12 (1.68-2.57)	2.52 (1.95-3.08)	2.88 (2.18-3.55)

Figure 17. Precipitation Frequency Estimates from NOAA Atlas 14, produced by the NWS HDSC for the Weiser Wash. Weiser Wash recorded at least a 1000 year ARI (0.1% AP) with a storm total accumulation of 118.11 mm (4.65 inches) for this event, outlined in red. The vast majority of that rain fell within 3 hours. During one 15-minute increment, the Weiser Wash recorded 30.48 mm (1.2 inches; as seen in Fig. 18), which is at least a 200 year ARI (0.5% AP) for that 15 minutes, outlined in green.

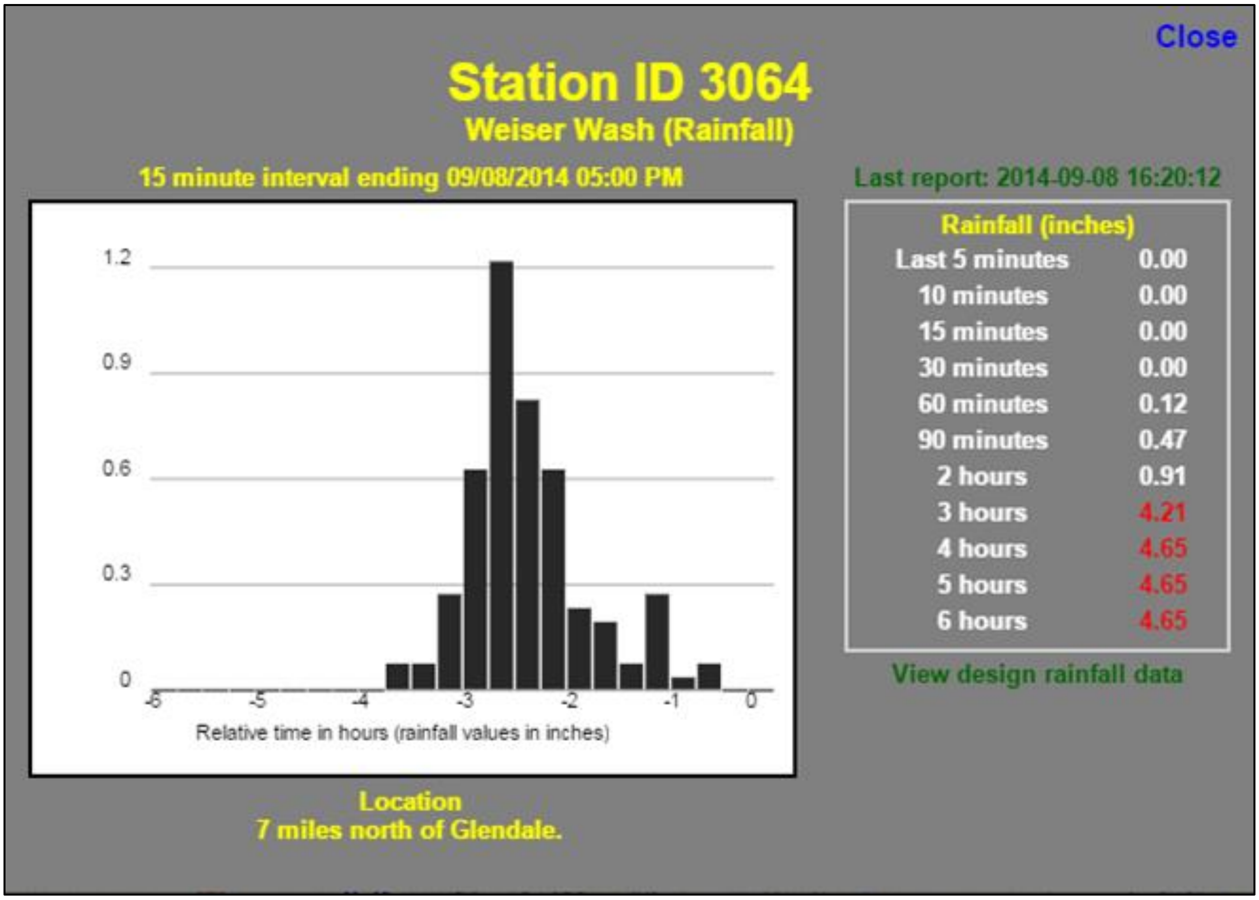

Figure 18. Clark County Regional Flood Control District rain gauge located in Weiser Wash illustrating the rainfall accumulations in 15-minute increments, ending at 5:00 PM PDT. Storm total rainfall accumulation was 118.11 mm (4.65 inches), with one 15-minute time period accumulating 30.48 mm (1.2 inches).

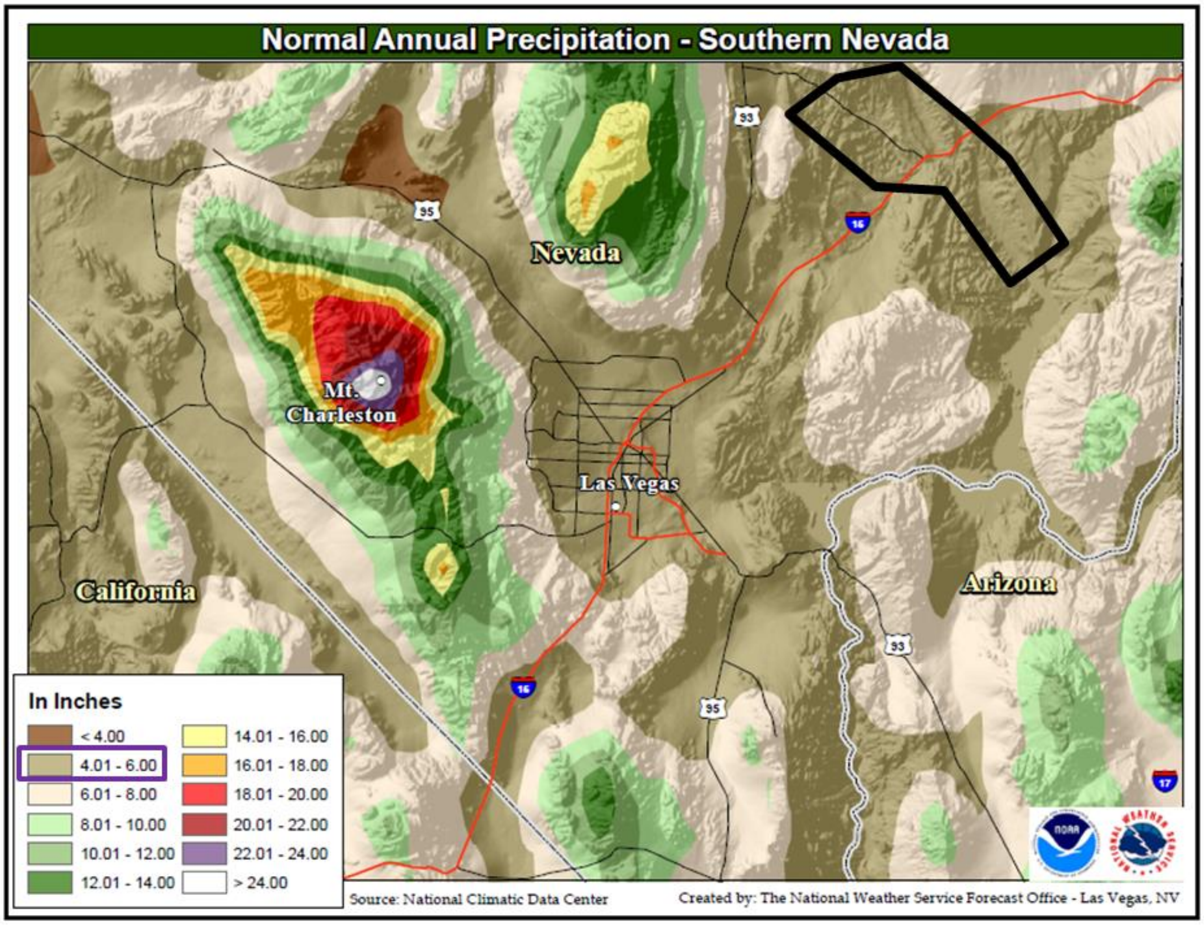

Figure 19. Normal Annual Precipitation across southern Nevada, created by NWS Las Vegas. Moapa Valley is outlined in black, which typically experiences between 101.85 and 152.4 mm (4.01 and 6 inches) of precipitation annually, as outlined in purple within the legend.

NWS Las Vegas: Norbert to Spread Moisture into the Area

Issued: 3:20 PM PDT Friday, September 5th, 2014

NWS Las Vegas can be contacted 24/7 at 702-263-9750 or on Twitter @NWSVegas

Updated to include the issuance of a Flash Flood Watch from 10 am Sunday morning through 4 am Tuesday morning. Areas included in the watch are all of Clark and Mohave Counties, southern Nye County, the high dessert of San Bernardino and eastern Inyo Counties.

OVERVIEW

Hurricane Norbert continues to move north-northwestward paralleling the Baja. The hurricane is currently forecast to weaken to a Tropical Depression Sunday night or early Monday as it moves over cooler waters and encounters drier air. High pressure to the east will help pull moisture from the remnants of Norbert northward into the area, rapidly increasing chances for showers and thunderstorms…that may linger through at least Tuesday. Models now agree with mostly dry conditions by the middle of next week. For those interested in tracking storms across the Eastern Pacific including Hurricane Norbert, please visit the National Hurricane Center website at: http://www.nhc.noaa.gov/?epac

PRIMARY AREAS IMPACTED & TIMING

- **SUNDAY-TUESDAY (MODERATE-HIGH Confidence):** A significant increase in moisture is expected across the area aided by the remnants of what is currently Hurricane Norbert. The primary areas of concern for significant rainfall are across Mohave, Clark and eastern San Bernardino Counties. Rainfall amounts/rates could be high enough to greatly increase the flash flooding threat across these areas, potentially both day and night. Confidence in moisture reaching the far western and northwestern forecast area remains lower. There is now higher confidence in the deeper moisture reaching into Lincoln County…especially Monday into Tuesday where the flash flooding threat is increasing. Changes are still possible to the forecast as the track of Norbert's remnants remains uncertain.

IMPACTS

- The primary concern will be the potential for localized heavy rainfall which may trigger flash flooding, particularly around burn scars such as Carpenter 1 and Dean Peak.
- Gusty & erratic winds near stronger activity could raise significant dust and reduce visibility.

CONFIDENCE

MODERATE-HIGH: In the development of heavy rain producing showers and thunderstorms.

LOW-MODERATE: In the timing and placement of precipitation and any areas of flash flooding.

FLASH FLOOD THREAT INDEX

	Burn Scar	Sat 9/6	Sun 9/7	Mon 9/8	Tue 9/9	Wed 9/10	Thu 9/11
T-storm/Flash Flood Threat Index	Carpenter 1	20	50	60	40	10	5
	Dean Peak	30	70	70	50	20	5

*Index numbers represent the threat of flash flooding over the burn area. Numbers run from 0-100. Values over 50 indicate that a Flash Flood Watch is possible, while lower numbers mean conditions are marginal. These numbers DO NOT indicate flash flood severity.

Figure 20. An example of NWS Las Vegas internal email briefings that were sent to Emergency Management and First Responders leading up to the 8 September 2014 Flash Flood.

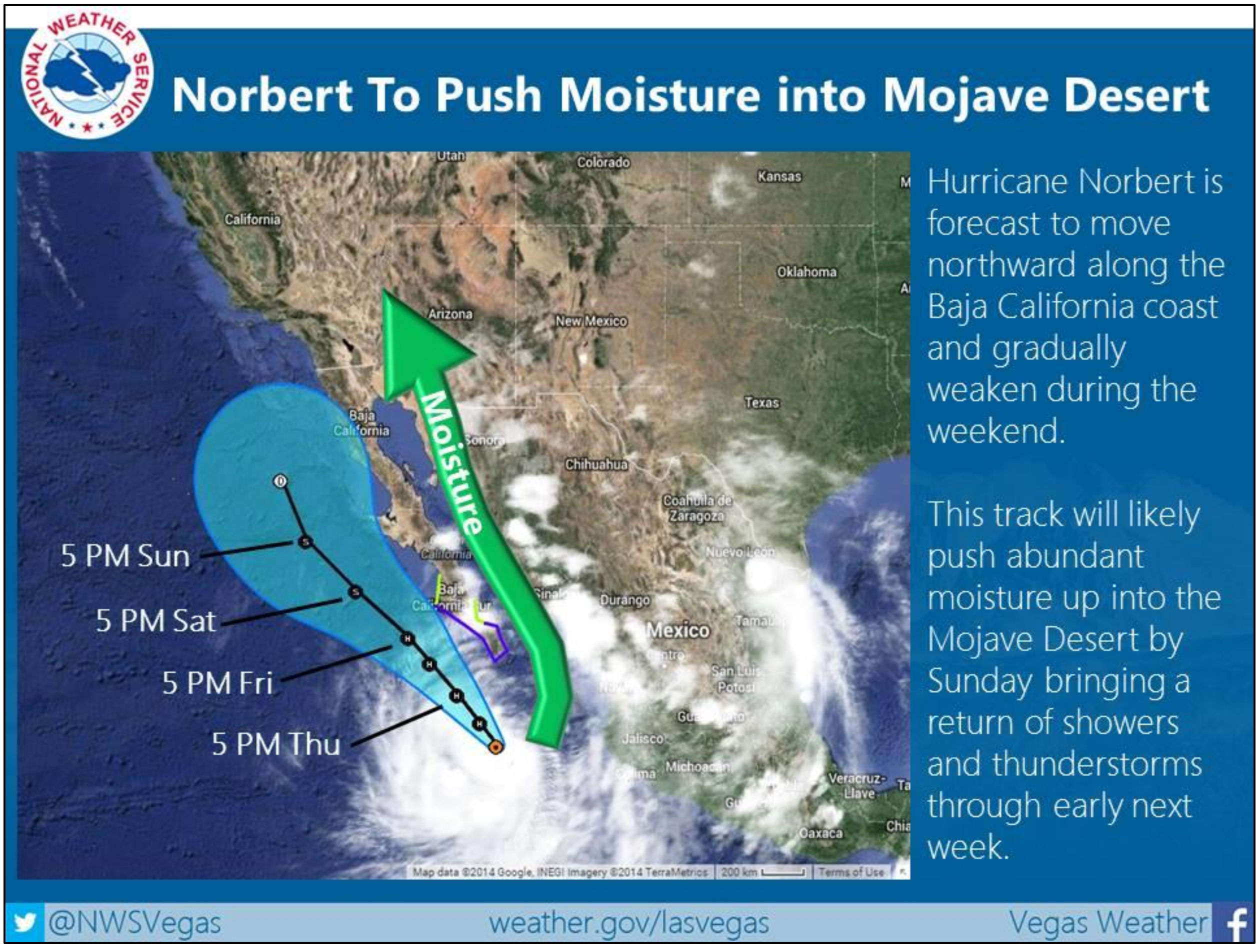

Figure 21. The initial graphic posted to social media on 3 September 2014 highlighting the potential for thunderstorms associated with moisture from Norbert. Subsequent graphics in the days leading up to the event featured details on timing and location of thunderstorms and forecast confidence.

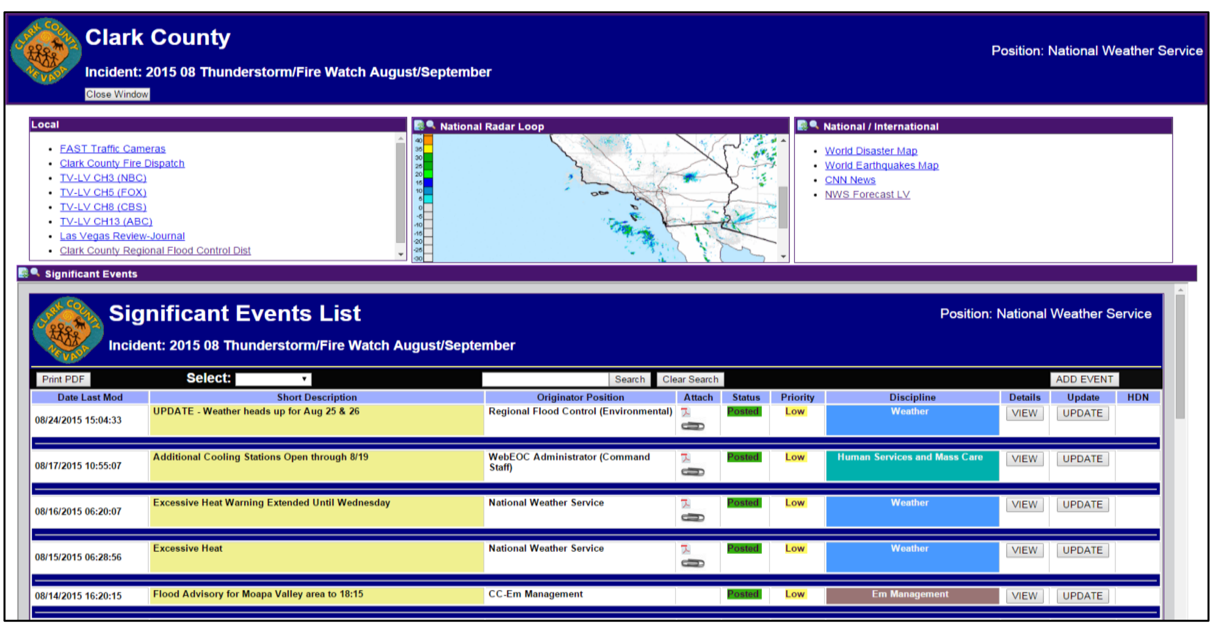

Figure 22. An example of the Clark County Web EOC interface, taken from August 2015 events.

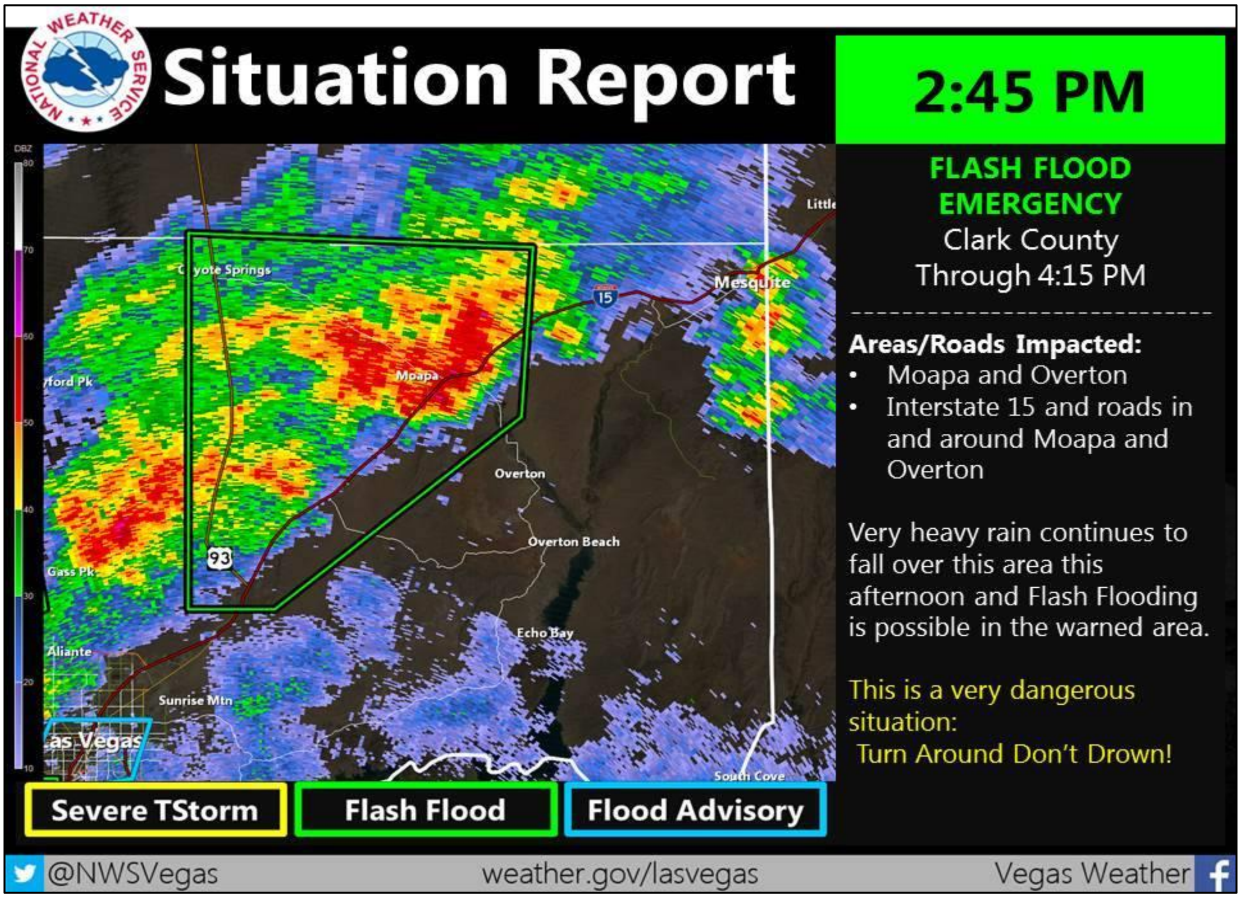

Figure 23. Situation report issued via Facebook and Twitter following the issuance of a Flash Flood Emergency for Moapa Valley and surrounding areas.

Figure 24. Photo courtesy of Nevada Highway Patrol showing the Interstate 15 damage, closure, and cleanup operations. Flood water flowed from right to left in this picture.

Figure 25. Photo courtesy of Nevada Highway Patrol showing a substantially damaged section of Interstate 15.

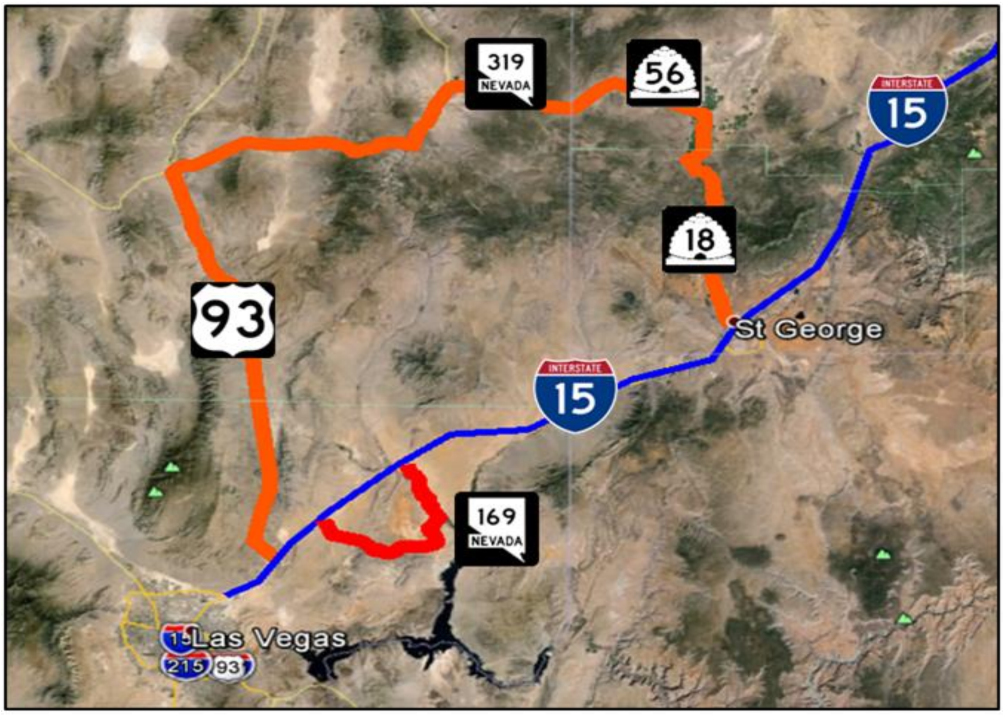

Figure 26. Map denoting the alternate routes available for travelers during the Interstate 15 closure. Routes in orange were used to get from Las Vegas to St. George, whereas Nevada 169 through Valley of Fire State Park was the only option for locals to navigate around the Interstate closure.

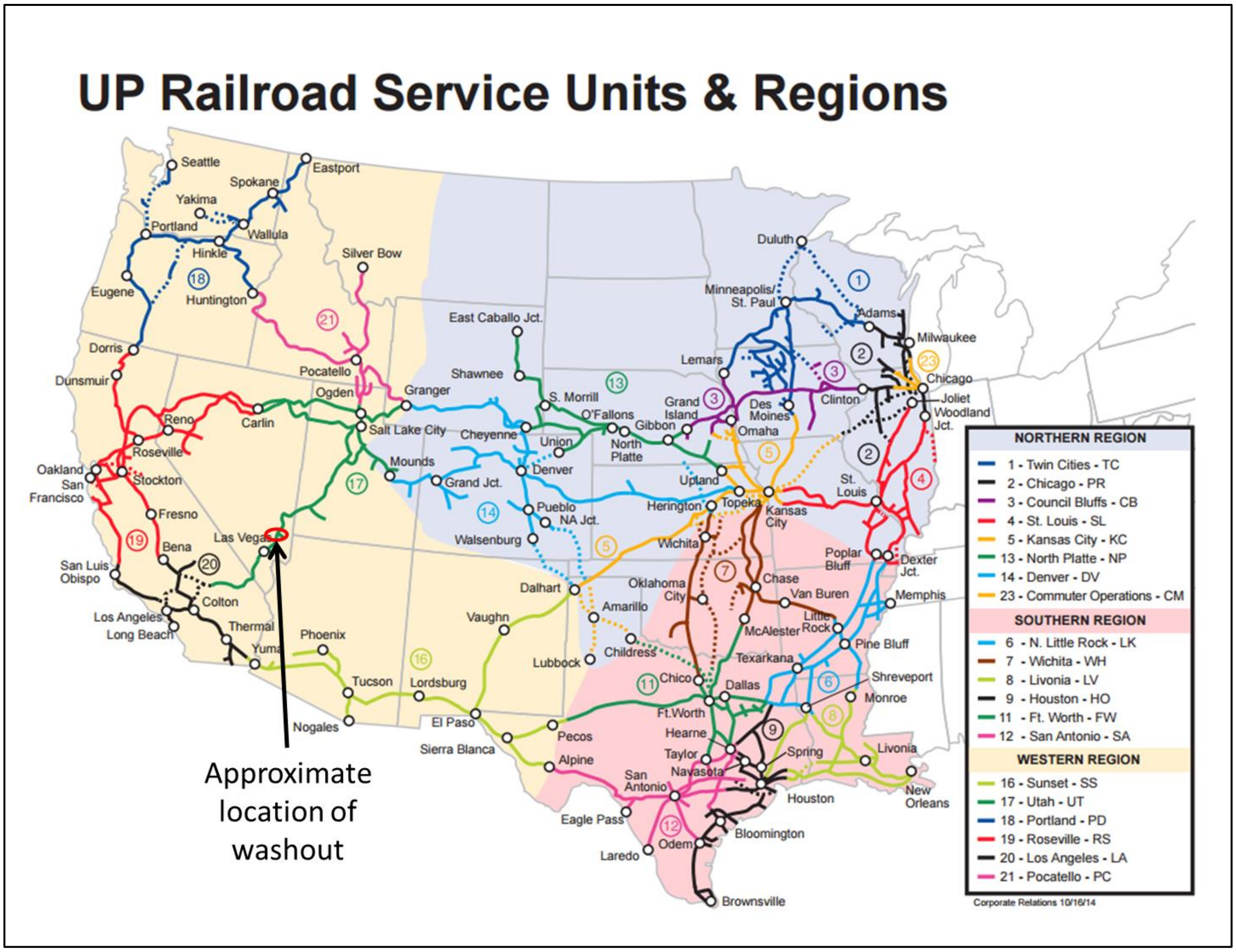

Figure 27. Union Pacific track network and associated regions. The critical Caliente Subdivision is located between Las Vegas and Salt Lake City. The approximate location of the washout is denoted by the red circle, which effectively cut off all rail transportation from Los Angeles to Salt Lake City.