Use of Radar-Rainfall Estimates to Model the January 9-10, 1995 Floods in Sacramento, CA

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Introduction

A long stream of warm subtropical Pacific moisture poured into California during the first half of January 1995. From January 1-12, rain fell somewhere in the state every day causing major flooding on the fourth, eighth, ninth, and tenth.[1] Sacramento and western Placer Counties were particularly hard hit during the evening of January 9 and early morning hours of January 10. Record rains fell at many locations and, in some areas, the 2-3 hour rainfall exceeded the 500 year event[2] while the recurrence interval for at least one storm total was computed to exceed 4,000 years.[3]

The intense downpours overwhelmed storm drain inlets causing severe and widespread street flooding. Streets, yards, and houses that had never experienced flooding were quickly inundated. Small streams and creeks also reacted immediately. By the morning of January 10, all of the major local waterways (Dry Creek, Arcade Creek, Morrison Creek etc.) overflowed - inundating adjacent properties to disastrous levels for the second time in nine years.

Flood damages exceeded $175 million in northern California. Sacramento and Placer Counties were just two of the 42 California counties included in the federal disaster declaration resulting from the January 1995 floods.

In terms of potential economic impact and numbers of people threatened, Sacramento has one of the highest levels of flood risk of any city in the nation. The region currently faces a number of very difficult policy decisions regarding flood control and flood plain management.

From the magnitude of the rainfall and resulting flooding, local officials concluded that the region's second flood disaster in nine years could have a significant impact on policies guiding local flood risk management. Investigations were launched immediately to assess the January storm, to evaluate data collected since 1986, and to revisit flood plain policies established in the aftermath of the 1986 disaster.

Post Storm Analysis

As soon as the flood waters subsided, Sacramento area governments initiated a series of hydrologic and hydraulic assessments. Lead by Sacramento County, local agencies, consulting engineering firms, and the US Army Corps of Engineers were brought together to set common objectives, to coordinate post storm analyses, and to provide a forum for peer review.

Objectives

The objectives of the post storm analysis of the January 1995 flood episode include:

- Provide the best available information for FEMA map revisions,
- Determine the impacts on the design of proposed flood control projects,
- Determine the impacts on federal cost sharing for proposed flood control projects, and
- Evaluate the new data and potential impacts on local flood plain management policies.

Methodology

The January 1995 flood event marked the first time data from a dense automated rain gauge network was available to analyze a major storm in the Sacramento area. In addition, radar-rainfall estimates based on new National Weather Service WSR-88D radar observations of the storm were available.

A preliminary analysis of the radar data showed that a major rainfall feature was positioned in a narrow gap in the local rain gauge network. It was obvious that, without the radar data, the post-storm analyses based on rain gauge data alone would have been unlikely to accurately depict the actual distribution and timing of the heaviest band of rainfall across the area. With both data sets available, it was decided to merge the two data sets to create a single gauge-adjusted radar-rainfall data set that would be the definitive rainfall data set for the post-storm analyses.

Watershed hydrology was modeled using US Army COE HEC-1 watershed model. The HEC-1 has been used throughout the Sacramento area for hydrologic analyses. All of the major Sacramento area waterways had HEC-1 model implementations calibrated and available for use in this study. The US Army COE HEC-2 model and the RMA-2 model were used to compute water surface profiles to compare with surveyed high water marks.

Study Areas

The principal drainages studied in the post-event analysis include the Dry Creek, Arcade Creek, and Morrison Creek watersheds. Additional study areas include the Natomas East Main Drain stream group and numerous smaller drainages throughout Sacramento County and western Placer County. The results obtained for the hydrologic analysis of Dry Creek, an area of particularly severe flooding, are the focus of this paper. (See Figure 1)

Dry Creek is a 101 square mile watershed located along the common border between Sacramento and Placer County in Central California.[5] The upper watershed drains relatively steep terrain with elevations falling from about 1200 feet msl in the eastern end to 110 feet msl at the western edge of the City of Roseville. Southwest of Roseville, Dry Creek transits a very flat and hydraulically complex region on its way to the Natomas East Main Drain Canal and the Sacramento River.

Rainfall Estimates

Rain Gauge Network

The last major flood in the Sacramento area occurred in February 1986. Virtually no continuous rainfall records were available at that time for detailed post-event analyses in Sacramento and Placer Counties. Since 1986, Sacramento County, Placer County, the City of Sacramento, the City of Roseville, and the National Weather

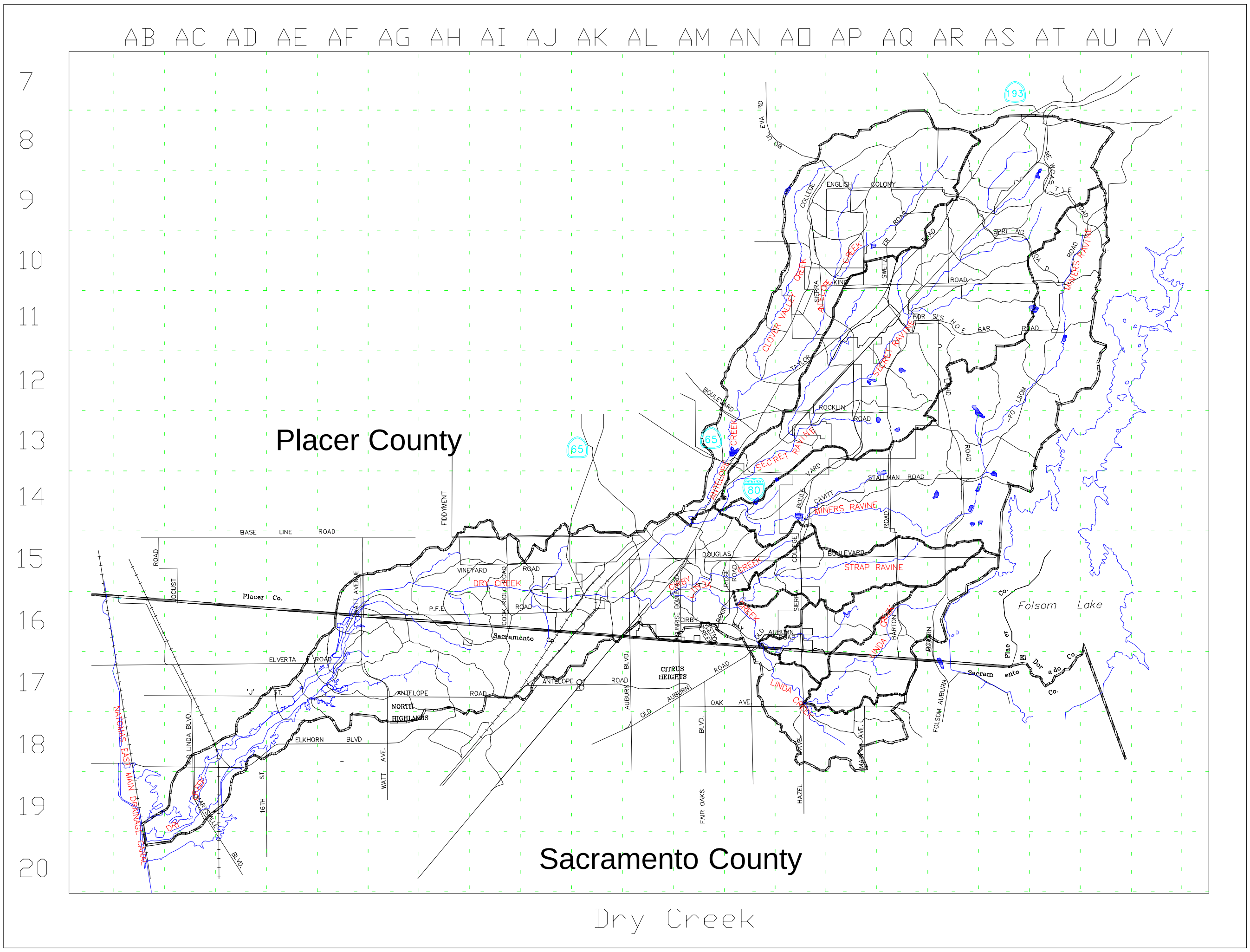

Figure 1: Dry Creek watershed.

Service have installed more than 40 ALERT-style rain gauges. These 12 inch diameter tipping bucket gauges, automatically report rainfall measurements in 1 mm increments by radio to computerized receiving stations. A total of 43 rainfall records were available in the Sacramento area for the January 9-10 storm. Twenty-three stations were used in the analysis of Dry Creek.

Radar-Rainfall Estimates

Radar Coverage

During the year prior to the January 1995 flood event, several National Weather Service WSR-88D radar systems covering portions of California were installed. Figure 2 shows the coverage areas (230 km radius) for the radars of interest operating in January of 1995. Note that three radars, Sacramento (DAX), Monterey (MUX), and Reno (RGX), cover the Sacramento area.

Of the three available NWS radars, the Sacramento radar, with its transmitting antenna located just a few miles southwest of downtown Sacramento, had the best view of the storms producing the January 9-10 floods. Both the Monterey and Reno radars were too far away to be of much help. In addition, the Sierra-Nevada Mountains rise to more than 8,000 feet msl between Sacramento and Reno, effectively blocking much of the radar signal from Reno.

NWS WSR-88D Radar-Rainfall Estimates

The WSR-88D radar systems are equipped to estimate rainfall on a 2 km x 2 km (approximate) grid. Radar-rainfall estimates are prepared in the form of color images representing accumulated rainfall for one hour, three hours, or storm totals. Each rainfall grid or pixel is assigned a color indicating the rainfall range for that pixel in that time period. For example, one color might indicate a rainfall total of between 1.0 in. and 1.5 in. for the period. Exact representations of the radar-rainfall estimates are not available from these images. Figure 4 shows a WSR-88D display image of three hour accumulations for the period ending at 7:08 AM PST, January 10, 1995. Images of rainfall accumulations are only available at irregular times, making a precise definition of a rainfall time series for a given location virtually impossible.

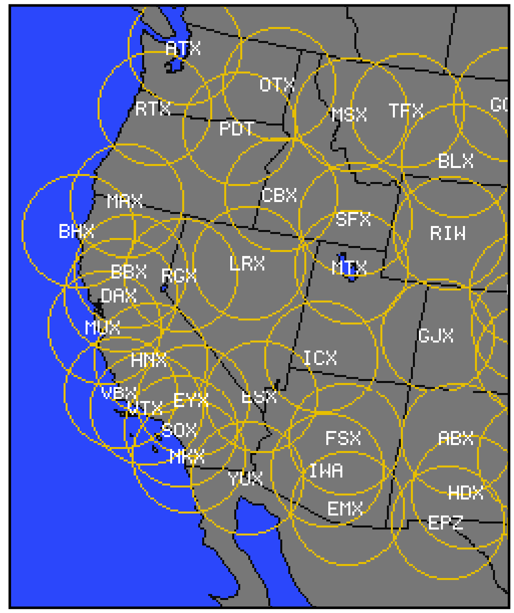

Figure 2: Coverage Areas (230 km dia.) for NWS WSR-88D Radars, January 1995

To create rainfall data suitable for hydrologic modeling, the WSR-88D radar system is designed to produce a Digital Precipitation Array. The Digital Precipitation Array contains radar-rainfall estimates on a 4 km x 4 km grid with a time resolution of one hour.

Since the Sacramento WSR-88D was very new in January 1995, not all of the precipitation products were available. Hourly images of accumulated rainfall were obtained that covered most of the periods of heavy rain on the evening of January 9 and the morning hours of January 10. A three hour storm total was obtained for the period ending at 7:08 AM on January 10 (See Figure 4). The Digital Precipitation Array was not available.

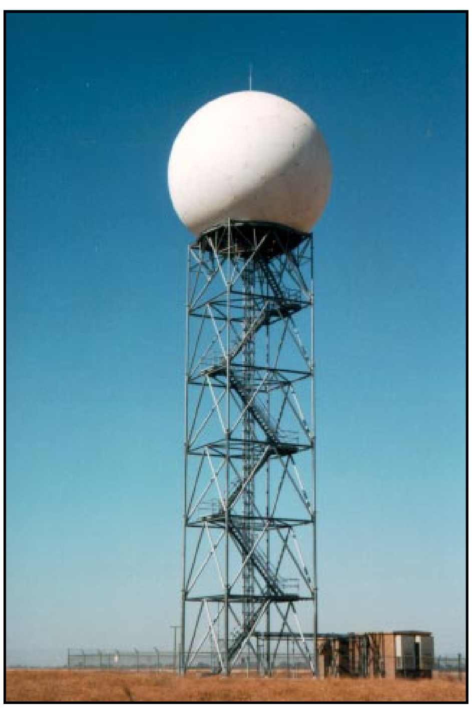
Figure 3: NWS WSR-88D, Sacramento, CA

WSI Radar-Rainfall Estimates

The WSI Corporation of Billerica, MA, is a value-added weather information supplier and a distributor of WSR-88D data. WSI ingests radar reflectivity data from all NWS conventional and WSR-88D radars across the country in real-time and merges the data into a national radar image. Using the national reflectivity data, WSI employs a proprietary dynamic weather condition-based algorithm to convert radar data into rainfall estimates on a 2 km x 2 km grid every 15 minutes[6]. WSI's radar-rainfall estimation product is called PRECIP.™

Since February of 1993, WSI has archived all of these rainfall estimates for the entire country where radar coverage is available. Thus, a continuous record of 15-minute accumulated radar-rainfall estimates for each 2 km x 2 km pixel (approx. 950 acres) suitable for input to a hydrologic model was available.

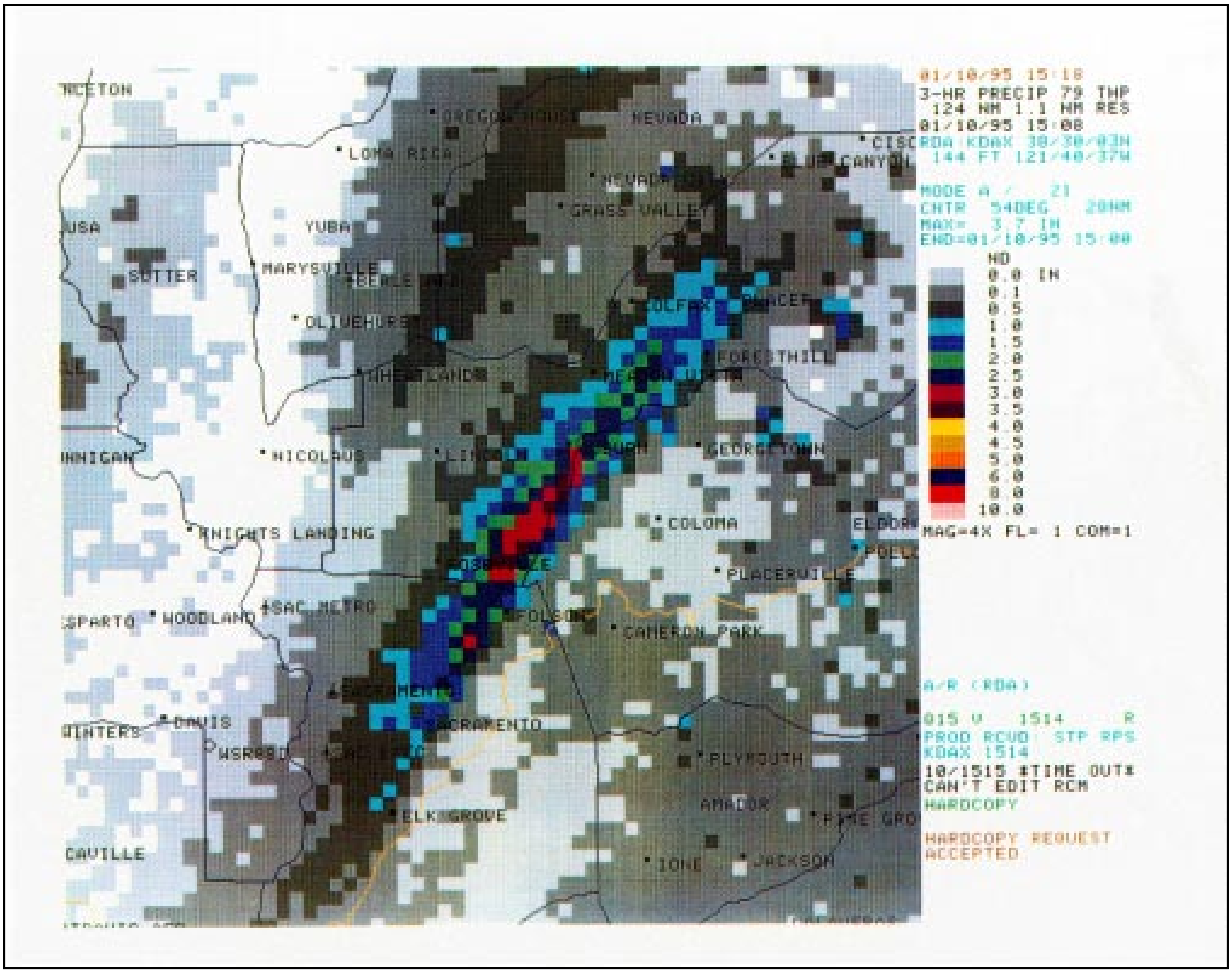

Figure 4: Sacramento NWS WSR-88D three hour accumulations ending at 7:08 AM PST

Radar-rainfall estimates were obtained from WSI for an area defined by a 1° latitude by 1° longitude box (38-39N, 121-122W) enclosing Sacramento County the western portions of Placer County containing the Dry Creek watershed.

Rainfall Distribution

The storm event of January 9-10, 1995 was composed of three distinct phases. Each phase produced dramatically different rainfall patterns.

The first major storm segment hit the Sacramento area during the evening hours of January 9. Heavy rains associated with a frontal passage occurred between 6-12 PM PST. The bands of heavy rainfall moved steadily across the region and rainfall amounts were fairly uniform. Figure 5 shows a 3-D contour plot of the rainfall distribution over a rectangular area enclosing the Dry Creek watershed. Rainfall amounts were in the 1-3 inch range for the period.

Around 3 AM on January 10, the heavy rain picked up again as a stationary line of thunderstorms began to pummel the eastern portions of Sacramento County and the upper reaches of Dry Creek in Placer County. For more than three hours, pulses of moisture moved along the stationary storm axis dumping heavy rain. Rainfall amounts were highly variable during this phase of the storm - ranging from less than 0.5 inches in western Sacramento County to nearly 4 inches in eastern portions of Sacramento County and the upper reaches of Dry Creek. Figure 6 shows the 3-D contour plot for rainfall accumulations during the second major storm segment.

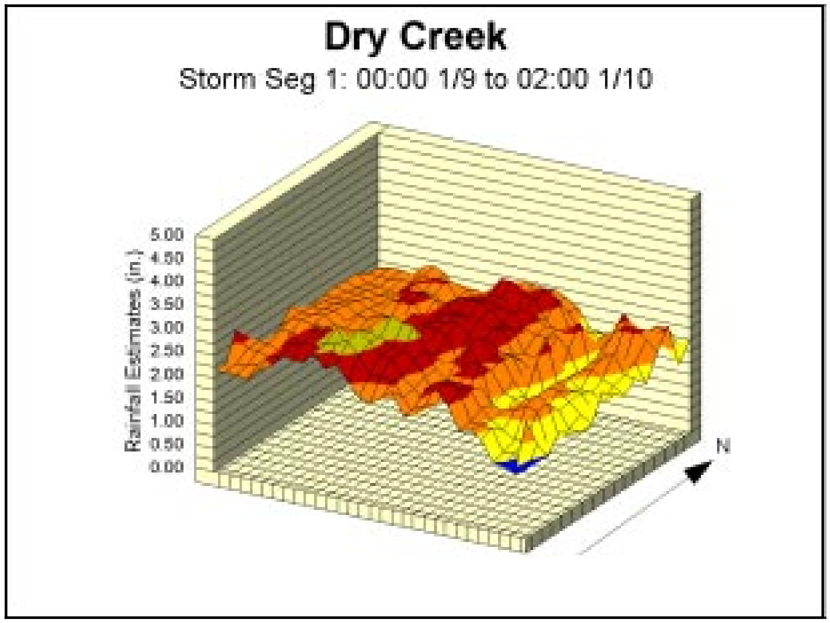

Figure 5: 3-D Rainfall Contour Plot for Storm Segment 1

The third phase of the storm event occurred during the afternoon hours of January 10. Daytime heating triggered scattered downpours throughout the area. Figure 7 shows that most of the area received less than 1 inch of additional rainfall. However, isolated downpours dropped 1.5-2.0 inches in three different locations.

Rainfall Adjustments

Background

Rain gauges and radar are two fundamentally different tools used to estimate the volume of rain falling on a watershed. Rain gauges make *direct* measurements over a very small area. (just 28 billionths of a square mile for a 12 inch diameter rain gauge) Estimates of areal rainfall are *indirectly* estimated by making assumptions regarding the amounts of rain falling between the gauges.

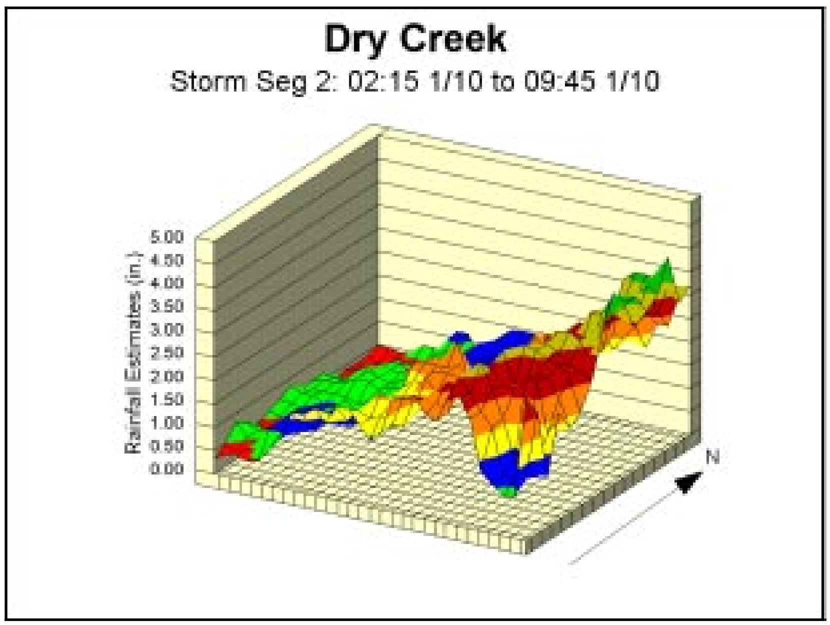

Figure 6: 3-D Rainfall Contour Plot for Storm Segment 2

Conversely, radar is used to *indirectly* infer rainfall amounts from *direct* areal measurements over a 2 km x 2 km pixel - an area 53 million times larger than a 12 inch diameter rain gauge. Radar measurements are continuous over the entire watershed. Speculation about the variability of rainfall over a watershed is virtually eliminated.

Since rain gauges and radars are fundamentally different tools used to estimate rainfall, direct comparison of rain gauge estimates and radar estimates of rainfall is not straightforward. Radar estimates are estimates of the *average* rainfall over the entire 2 km x 2 km pixel. Rain gauges estimate rainfall at a *point*. Within a given pixel, the rain gauge observation is a function of the gauge's location within the pixel. Figure 8 shows the "true" distribution of rainfall along one slice across a radar pixel. The radar estimate is the average across the entire pixel but the rain gauge measurement depends on the gauge's location along the slice. Both observations can be correct yet significantly different.

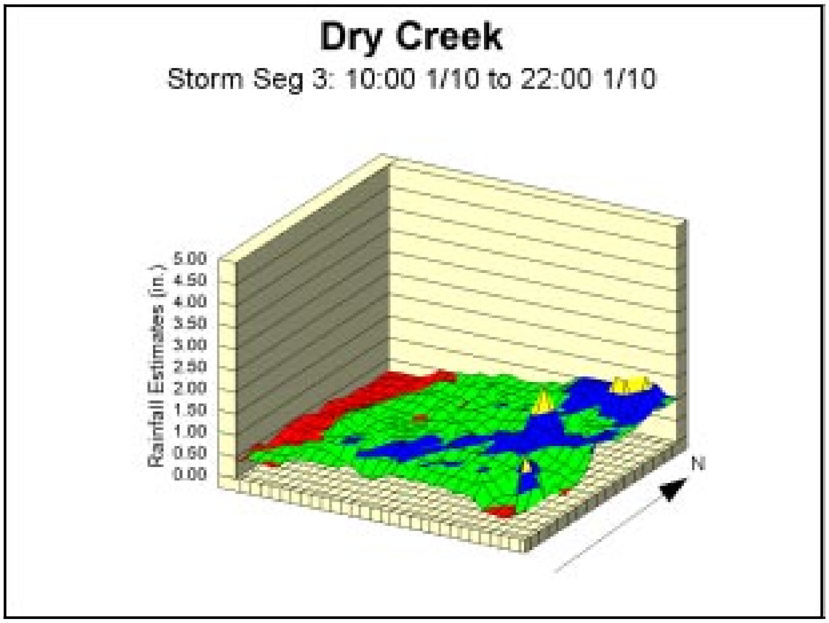

Figure 7: 3-D Rainfall Contour Plot for Storm Segment 3

Wind Adjustments to Rain Gauge Measurements

Although rain gauges are by far the most common method used to measure rainfall, rain gauges are subject to errors. Wind effects, mechanical problems, calibration errors, etc. can all affect the accuracy of rainfall records.

A major contributor to rain gauge errors and inconsistent measurement is wind. Wind effects are undoubtedly the biggest source of error in properly maintained and functioning gauges.

The scientific literature is filled with references to precipitation gauge under-catch due to wind. In a recent article in the Bulletin of the American Meteorological Society[7], researchers reported that the nation's climatic network underestimates total precipitation by 10-40%, depending on precipitation type.

Many researchers have proposed wind correction techniques and the World Meteorological Organization[8] has published a variety of sophisticated wind correction methodologies. Peck and Larson[9] offer a relatively simple approach as they report observed under-catch for unshielded rain gauges as approximately 1% per mile per hour of wind speed at the gauge orifice. In other words, a 10 mph hour wind at the gauge orifice causes an estimated 10% under-catch.

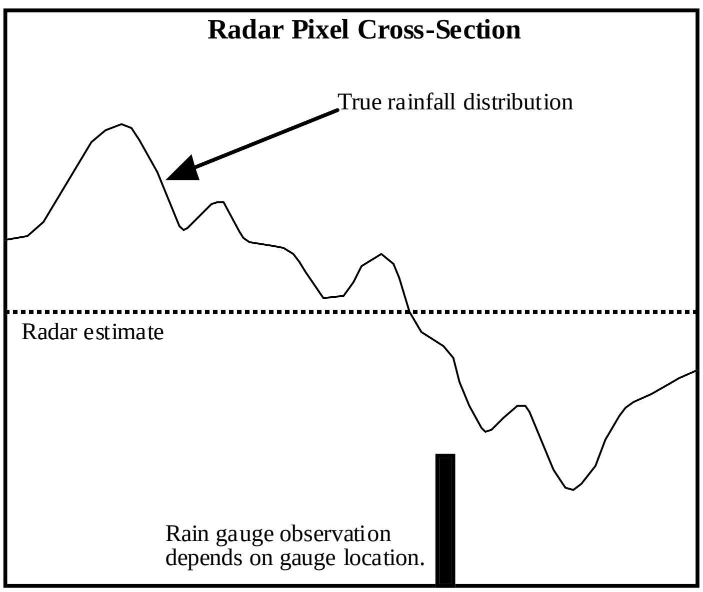

Figure 8: Comparison of radar and rain gauge observation

The affect of wind on rain gauge measurements was a concern during the January 9-10 event. Wind speeds during the storm were, at times, sufficient to cause significant errors in rain gauge measurement. Figure 9 shows the wind records at five locations during the storm. Winds were in the 20-45 mph range for several hours. Since wind speeds were so high, the decision was made to adjust the rain gauge observations to account for the effects of wind.

Since wind records were only available at five locations, it was necessary to estimate wind speeds at the other rain gauge sites. A visual inspection of Figure 9 suggests that the wind speeds were fairly well correlated. In other words, periods of high wind speeds and periods of low wind speeds occurred at about the same time at all sites.

Wind observations are heavily influenced by the relative exposure of the wind gauge to the general wind field. Some gauges are heavily sheltered and protected by surrounding trees and buildings. Other sites, such as Sacramento Metro Airport and Folsom Dam are highly exposed with little or no protection from the general wind field. Sheltered or low exposure sites tend to report lower wind speeds than unsheltered or high exposure sites.

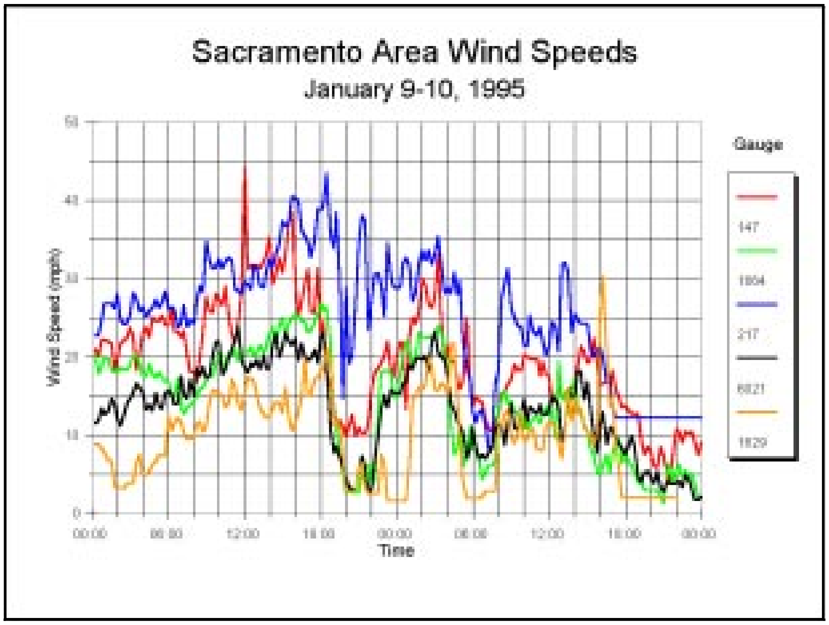

Figure 9: January 9-10 wind speeds

Wind exposure indices were developed for each rain gauge location in Sacramento and Placer Counties. Wind exposure indices were based on a 1990 review of Sacramento County ALERT rain gauge locations[10]. Wind indices were updated for 1995 conditions in Sacramento County and were estimated for new sites based on input from Sacramento County ALERT network maintenance personnel familiar with the sites. Wind indices for a representative sample of sites in the City of

Table 1: Wind Exposure Indices (WEI) for Rain Gauge Locations

Gauge	ID	WEI	Gauge	ID	WEI
NWS Metro	150	7	DO5/Basin	1674	6
Cresta Park	267	3	Corabel/Chicken Ranch	1681	1
Eagles Nest/Laguna Creek	269	5	Alpine/Unionhouse Creek	1724	4
Elk Grove	270	4	Elder Creek/Stockton Blvd.	1734	6
Georgiana Slough	271	5	Folsom Mormon Dike	220	8
Gerber/Elder Creek	273	1	Roseville Fire Station	1602	2
Metro Airport	274	3	Target	1604	5
Navion	275	2	Miners Ravine	1608	5
Orangevale	276	3	Moss Lane	1610	1
Rancho Cordova	277	4	Del Oro H.S.	1612	4
Rio Linda	278	3	Strap Ravine	1613	2
Chicago	279	2	New Castle	1614	6
Ione Road	280	8	Caperton Reservoir	1616	7
Arden/Chicken Ranch	281	4	Endora Lift Station	1617	4
Correctional Center	283	6	Sierra College	1618	2
Van Maren/Cripple Creek	286	3	Antelope Creek	1621	4
Prairie City	287	7	Loomis Observatory	1624	3
Sunrise/Arcade Creek	291	2	Champion Oaks	1628	5
ARC/Arcade Creek	295	1	Dry Creek @ Royer Park	1632	3
Linda Creek/Indian Creek	299	3	Morrison City	1687	4
Beach Lake/Morrison	1652	3	Arcade City	1690	4
Lambert Road	1658	3	Roseville Waste Water TP	6024	8
Elkhorn	1659	4	Roseville Water Plant	6032	7
Branch Center	1667	3	Diamond Oaks	1601	3
Strong Ranch Slough	1673	2			

Wind Exposure Index Key:

1 Full shelter by close vegetation (95-100%)
2 Nearly full shelter by close vegetation/structures (60-95%)
3 Partial shelter by close vegetation/structures (30-60%)
4 Partial shelter by distant vegetation/structures (60-100%)
5 Partial exposure with distant vegetation (30-60%)
6 Nearly full exposure (60-95%)
7 Full exposure (95-100%) equivalent to airport exposure
8 Heightened exposure (top of hill or building)

Roseville were established during an on-site review. Wind indices for remaining sites were estimated by ALERT technicians familiar with each location. The final wind indices are shown in Table 1.

Wind speed at each location lacking wind records was estimated by interpolating between the average 15 min. wind speed measured at high exposure sites and the average 15 min. wind speed at low exposure sites. The wind speed index was used as the basis for linear interpolation and rain gauge under-catch was estimated at 1% per mph of wind.

The wind speed time series shows that during the periods of heaviest rainfall, wind speeds were lowest. Wind effects were greatest during periods of lighter rainfall when wind speeds were higher. Even though storm winds exceeded 25 mph for extended periods of time, wind corrections only amounted to a rainfall adjustment of 10-15% to rain gauge observations overall.

Radar-Rainfall Adjustments

As stated previously, a point gauge observation within a pixel is a function of its location. Radar-rainfall observations are estimates of the average rainfall over an entire pixel. Rain gauge observations and radar estimates for the pixel containing the gauge can significantly differ yet both estimates can be correct.

If there is just one pixel-gauge pair of rainfall estimates, there is no way of knowing whether or not the radar estimate is biased and in need of adjustment. However, if enough gauge observations are available, one can expect that some of the gauges would be in position to measure amounts higher than the radar estimated average and some gauges would measure lower than the radar estimated average. If the average of all gauge observations is approximately equal to the average of all the associated radar pixel estimates, the radar field is unbiased. If there is a significant difference between the average gauge value and the average radar pixel estimate, the radar field is assumed to be biased on average. The bias can be corrected by applying a “mean-field” field adjustment factor to each pixel in the radar field.

The mean field adjustment factor used in this study is defined as the ratio of the average rain gauge observation and the average radar-rainfall estimate for the pixels associated with each rain gauge location. Mathematically,

$$f(t) = \frac{\frac{1}{n}\sum_{i=1}^{n} g_i(t)}{\frac{1}{n}\sum_{i=1}^{n} r_i(t)} \tag{1}$$

where f(t) is the mean field adjustment factor at time, t, n is the number of gauge-pixel pairs, *i* indicates the i^{th} pixel-gauge pair, g(t) is the rain gauge observation at time, t, and r(t) is the radar observation at time, t.

The mean field adjustment factor was developed from pixel-gauge pairs located in and near the target watershed. Localizing the mean field adjustment factor reduces the potential impacts of any performance variations in the radar data set that are a function of location. (Ground clutter, anomalous propagation, and other artifacts may affect rainfall estimation in some parts of the area but not others.) By keeping the area used to develop the mean field adjustment factors to a minimum, the mean field adjustment factors are more representative of radar performance in the target watershed.

Time Averaged Mean Field Adjustment Factor

The mean field adjustment factor was computed for each 15 minute period during the storm event. However, at the beginning and end of an event as rain enters or leaves the area and during times of highly scattered rainfall, it is possible that all of the gauges report zero rain for a given 15 minute period. It is also possible to have valid rainfall in the vicinity that hasn't reached or isn't falling at locations with gauges. Under these circumstances, the average gauge value is zero which, according to Equation 1, eliminates valid rainfall observed by radar when the mean field adjustment factor ratio is applied.

To counter this problem, the mean field adjustment factor was averaged over five time periods (current period +/- two periods or 75 minutes total). Using a time averaged mean field adjustment factor to adjust the radar values significantly reduced the possibility of zeroing out valid radar data when gauge readings were zero. It also served to smooth the radar-rainfall adjustments from time period to time period and reduced the incidence of radical changes in mean field adjustment factor when the average radar value was small compared to the gauge observations. Equation 2 defines the time-averaged mean field adjustment factor, F(t).

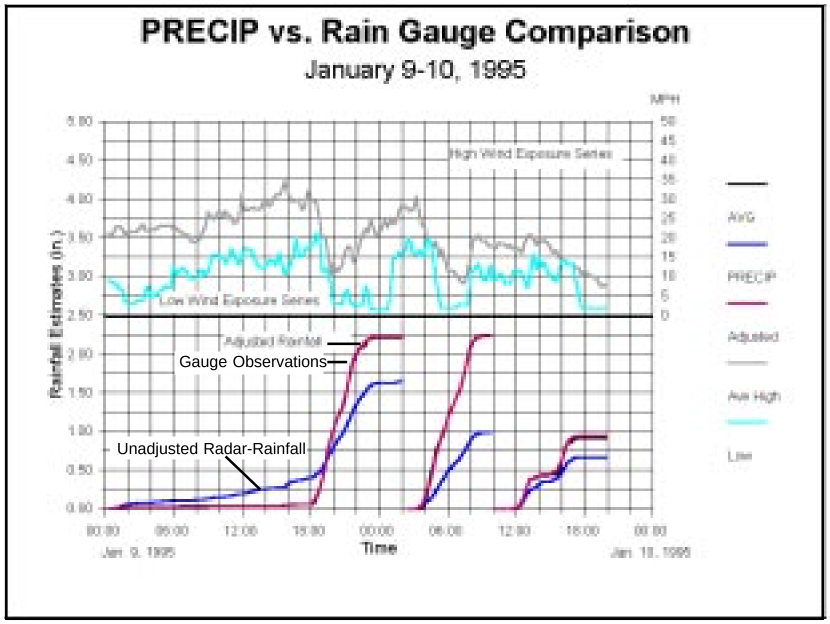

Figure 10: Dry Creek Average Radar-Rain Gauge Comparison

$$F(t) = \frac{1}{5}\sum_{t-2}^{t+2} f(t) \qquad (2)$$

Rainfall Estimation Results

After applying the mean field adjustment to each radar pixel, the volume of rainfall as represented by the radar pixels associated with rain gauges is exactly the same as the volume of rain represented by the rain gauge observations. Figure 10 shows the time series of the average unadjusted radar-rainfall estimates, the average rain gauge observations, and the average adjusted radar-rainfall estimates. In addition, Figure 10 shows the average high and low exposure wind speed time series used to adjust the rain gauge observations.

The average unadjusted radar-rainfall estimates are shown in blue and the adjusted radar rainfall amounts are shown in red. The average rain gauge values (adjusted for wind effects) are shown in black and are exactly superimposed with the average adjusted radar-rainfall values. The superposition of the average rain gauge values and the average gauge-adjusted radar-rainfall estimates verifies the earlier statement that the volume of rainfall as represented by the rain gauge observations is exactly the same as the volume of rain represented by the associated radar pixels.

As far as the gauge-pixel pairs are concerned, the two data sets are equivalent. However, the advantage of the gauge-adjusted radar-rainfall data set is that the radar data set provides a more natural view of what occurred between the gauges than other available methods for distributing rainfall such as Thiessen or other rainfall weighting schemes[11].

Conceptually, the raw radar data is simply used as a template to describe the areal variability of rainfall over the watershed in space and time. Merging the radar template with the rain gauge observations yields a highly representative areal distribution of rainfall that's consistent volumetrically with the point rain gauge observations.

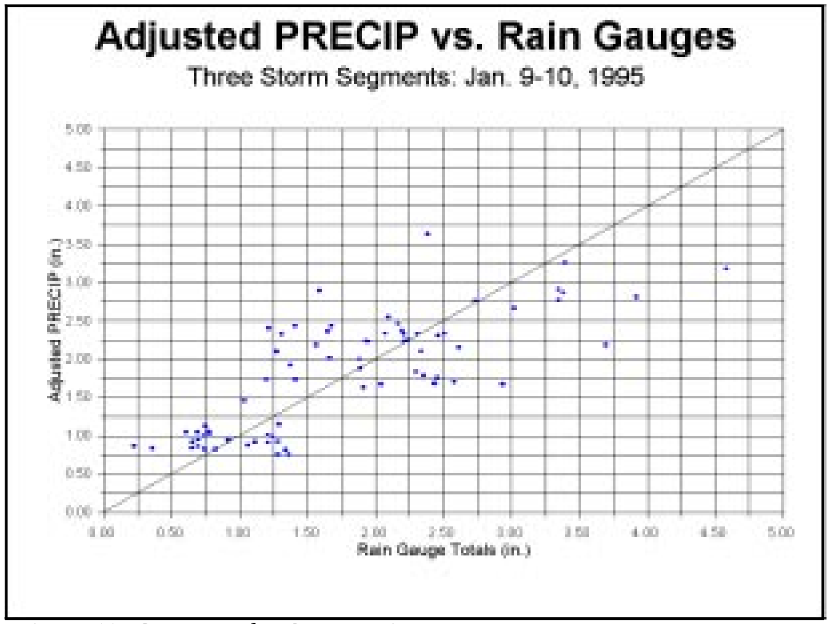

Figure 11: Gauge-Radar Scatter Diagram

Even though the average gauge-adjusted radar-rainfall estimate matches the average rain gauge value, there is still considerable variation in the individual gauge-pixel pairs. Figure 11 shows the scatter diagram comparing the individual gauge and radar pixel values for the three storm segments. The scatter of data points is normal and expected.

Hydrologic Analysis

Background

The HEC-1 model was used to simulate the hydrology of the Dry Creek watershed. Model setup, calibration, and use is documented in the *Dry Creek Watershed Flood Control Plan*[4].

The HEC-1 model was developed by the US Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, in 1967. The current version, V4.0, was published in 1990. The HEC-1 model is designed to simulate the surface runoff response of a watershed to precipitation. This is accomplished by representing the watershed as an interconnected system of hydrologic and hydraulic components. Each model component represents a specific aspect of the rainfall-runoff process occurring in a portion of the watershed. A component may represent the runoff occurring in a sub-basin, the routing of flows down a channel, or the routing of flows through a reservoir. Description of the components of the model requires estimation of parameters which are based on land use, soils, vegetation, topography, and stream geometry. Model results are streamflow hydrographs at specified locations throughout the watershed.

In the 1992 Montgomery Watson implementation of HEC-1 on Dry Creek, the upper 80 square miles of the Dry Creek watershed were subdivided into approximately 100 sub-basins. The model was constructed based on 1989 aerial photography and was calibrated to the February 18-20, 1986 flood event as observed at the stream gauging station near Vernon Street in the City of Roseville. Rainfall recurrence intervals for the 1986 flood event ranged from 25-75 years depending on location and time frame within the watershed. At the Vernon Street gauge, the

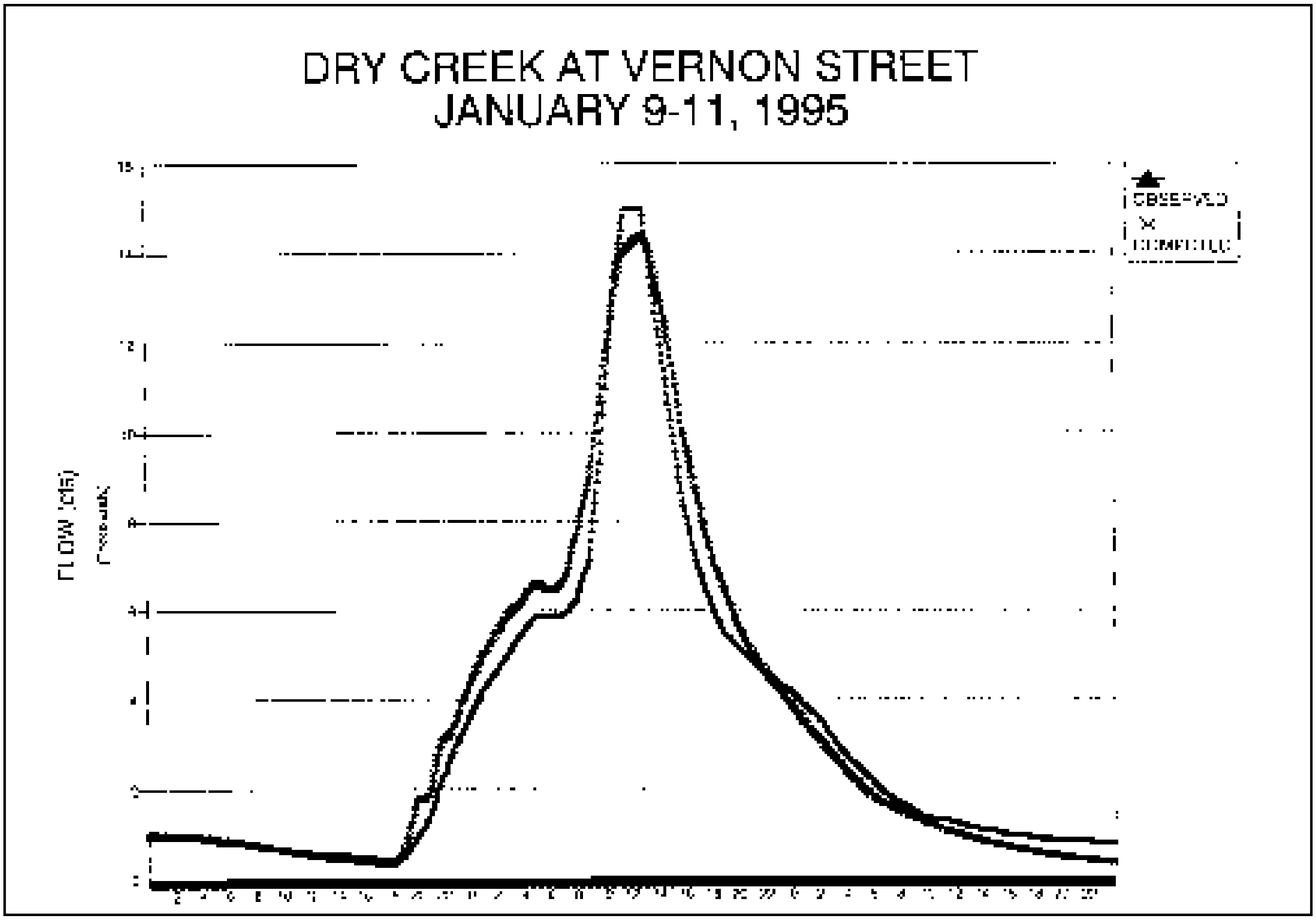

Figure 12: Simulated and Observed Hydrographs at Vernon St. in Roseville, CA

flow recurrence interval was approximately 75 years. The model was verified using a smaller flood event which occurred in January 1992.

Hydrograph Output

Gauge-adjusted radar-rainfall estimates for the January 9-10, 1995 event were used as input to the HEC-1 implementation for Dry Creek. Each radar-rainfall estimate represented the average 15-minute accumulated rainfall over an approximately 1.5 mi^2 pixel. A grid corresponding to the pixel locations was drawn on the watershed map and each pixel was associated with a model sub-basin. The radar-rainfall grid is shown in Figure 1. Average rainfall for each sub-basin was determined by the percentage of each radar-rainfall pixel covering a given sub-basin.

The first simulation attempt for the January 9-10, 1995 event used the same model parameters as were used for the February 18-20, 1986 event. The simulated peak matched the observed peak very closely. However, the rising limb of the hydrograph was too high, suggesting that a different initial loss condition existed for the 1995 event.

The initial soil moisture conditions for the 1986 event were assumed to be nearly saturated since the flood occurred near the end of several days of heavy rainfall. Although conditions were wet in 1995, soils weren't saturated to levels experienced at the start of the 1986 storm.

The initial loss parameter was changed from 0.1" to 0.8" for the second run. The resulting simulated hydrograph is shown in Figure 12 and compared to the observed hydrograph at the Vernon Street gauge.

The observed peak flows were determined from the observed stage record at the Vernon Street gauge, existing USGS ratings for lower flows, and a hydraulic analysis using HEC-2 to extend the rating. The preliminary estimate of the peak observed flow was 15,000 cfs but could easily be anywhere in the range of 14-16,000 cfs due to measurement errors.

The peak flow as simulated by HEC-1 was 14,500 cfs - well within the suspected range of the peak flow and within 3% of the proposed peak flow of 15,000 cfs. The overall hydrograph shape and timing were also very good. The estimated peak flood flow of 15,000 cfs is approximately the 100-year event at the Vernon Street gauge in Roseville.

Summary and Conclusions

Record floods hitting the Sacramento region for the second time in nine years prompted an intense round of post-storm analyses. New data sets, including measurements from a dense network of automated rain gauges and radar-rainfall estimates were available to support the post storm investigations. The rain gauge and radar-rainfall estimates were merged into one highly resolved (15 minute, 2 km x 2 km) gridded rainfall data set to provide a definitive description of the timing a distribution of rainfall for use in all post storm hydrologic analyses.

With 23 automated rain gauge records available for the 101 square mile Dry Creek Watershed, a strong argument could be made that the gauges alone should have been sufficient to describe the rainfall distribution. However, the radar data clearly showed rainfall patterns that could not have been inferred from the gauge network - especially the rainfall resulting from the stationary line of thunderstorms during the storm's second phase on the morning of January 10.

By combining the gauge and radar data sets, a definitive data set describing the areal distribution of rainfall was created that was volumetrically consistent with the point gauge measurements. In addition, the resulting gridded rainfall data was approximately the same resolution as the subwatershed structure of the HEC-1 model of Dry Creek. The hydrologic simulations produced from the gauge-adjusted radar-rainfall data set agree very closely with the observed hydrograph. Hydrograph volume, timing and shape were accurately reproduced suggesting that the volumetric representation of the areal rainfall was appropriate.

Properly estimating the distribution and timing of rainfall is one of the key elements of hydrologic analysis. Once the rainfall input is precisely established, the hydrologist is free to focus on fine tuning hydrologic model performance. Improved understanding of the areal nature of rainfall for a given event, allows the analyst to capture and evaluate the subtle timing and volume contributions of small subwatersheds to the composite watershed hydrograph.

The Dry Creek project is an excellent example of the practical use of the latest in radar technologies in rainfall estimation for hydrologic analysis. Gauge adjusted radar rainfall data sets with 15 minute 2 km x 2 km resolution is ideal for highly detailed distributed hydrologic analysis. It is also an excellent example of the combined use of new technology from a traditional source, the National Weather Service, and value-added data from the rapidly expanding third-party weather information market.

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