Comparing Spatial Distributions of Rainfall Derived from Rain Gages and Radar[1]

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Abstract

Traditional rainfall analyses for hydrologic modeling use spatial representations of rainfall derived from rain gage observations at a series of points. These gage-derived spatial representations of rainfall are computed using any number of techniques including inverse-distance squared weighting and more advanced methods such as Kriging. None of these techniques have any relationship with the real world or provide any information about the true spatial distribution of rainfall. They are simply methods of convenience used to interpret the spatial variation of rainfall from point data in the absence of other information or techniques.

Radar, on the other hand, offers a significant analytical improvement for rainfall analysis by providing direct data more representative of the true spatial distribution of rainfall. The differences between the spatial distributions derived from radar and those derived from rain gages are often striking and dramatic. Examples will be presented where the contours indicating general spatial trends are rotated nearly 90 degrees. These findings have significant implications for both modeling and for hydrologic standards that require data supporting design storm shapes and sizes.

Introduction

Rain gages are fundamental tools of the trade for hydrologists and water resource engineers. They provide an estimate of rainfall at a point, which is then used to infer the amount of rainfall over the area surrounding the gage. The success of this inference depends on how consistently rain gage observations actually represent rain falling in the area of interest.

Typically, a network of rain gages is used to determine rainfall patterns over a watershed or other target area. The network provides a collection of point estimates, which are used to map the spatial distribution of rain. The spatial distribution of rainfall is often described by a series of contours of equal rainfall known as isohyets, drawn through points interpolated from the rain gage observations. The shape of these contours estimates the shape of the rainfall surface over a region. Integrating over this surface yields the most important datum for hydrologists, the total volume of water entering a watershed. The accuracy of the estimate of total watershed input depends on how well rain gages estimate the actual rainfall topography.

The glaring weakness in a rain gage network's ability to define the actual rainfall surface is that rain gages can't provide any information about the rainfall distribution between gages. A network of rain gages can only resolve features of the rainfall surface larger than the characteristic distance between gages in the network. One would think, however, that a rain gage network would still be capable of identifying the larger scale shape and slope aspects of the rainfall surface. Surprisingly, as will be shown later in this paper, even the larger scale trends in the rainfall surface may be mischaracterized by standard rainfall interpretation techniques.

Radar-rainfall estimation offers hydrologists and engineers the opportunity to see between the gages. With resolutions on rectilinear grids down to 2-km x 2-km (4 km^2 or 1.5 mi^2), radar can resolve features on the rainfall surface in much greater detail. Rain gage network densities are rarely better than 1 gage per 10 square miles and 1 gage per 100 square miles or worse is more likely. With radar, it is possible to more accurately estimate the actual rainfall topography over a watershed. This leads directly to an improved estimate of the total watershed input as well as improved estimates of the timing and placement of input throughout the watershed.

The following sections compare and contrast spatial distributions of rainfall defined by rain gage networks and radar. The results are not surprising in that radar provides a much more detailed picture of rainfall distribution. However, what is surprising is the significant difference in large-scale features between radar and rain gage estimates. These differences may suggest new insights into rainfall distributions and may have significant consequences for hydrologic design standards.

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Spatial Analysis of Rainfall

In practice, a variety of techniques are used to interpolate rainfall at points between actual observations. For computer applications, a rectangular grid is placed over the target area and rainfall is estimated at each grid point. Inverse distance squared, Kriging, nearest neighbor, polynomial regression, and radial basis functions are common interpolation or surface fitting techniques used to estimate grid point values from scattered data. (Keckler, 1995) Inverse distance squared and Kriging methods are frequently used to contour rainfall. The nearest neighbor technique produces results equivalent to the well-known Theissen polygon method, as the grid point value is equal to the value of the closest rainfall observation. (See Ball and Luk, 1998 for a discussion comparing Theissen polygons, inverse distance weighting, Kriging, and two surface fitting methods: polynomial surfaces and spline surfaces.)

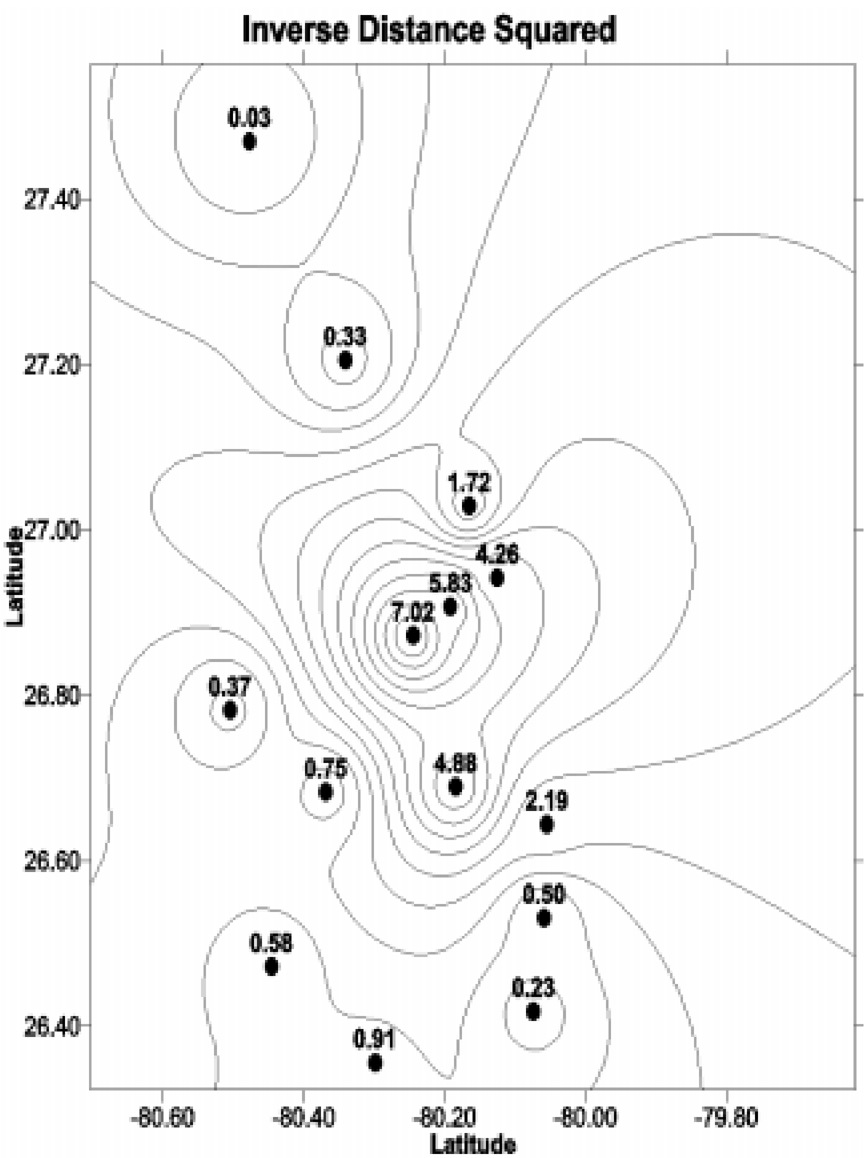

Figure 1: Rainfall contours derived from inverse distance squared weighting (Values are rain gage measurements in inches.)

The inverse distance squared techniques use equations of the form shown as Equation 1 to determine the rainfall at any given grid point. (Smith, 1993)

$$R_j = \frac{\sum_{i=1}^{n} \frac{1}{d_{ij}^2} r_i}{\sum_{i=1}^{n} \frac{1}{d_{ij}^2}} \qquad (1)$$

Where R_j is the rainfall estimate for the j^{th} grid point, r_i is the observation at gage i, d_{ij} is the distance from gage i to the j^{th} grid point, and n is the number of gages. Figure 1 presents rainfall contours derived using inverse distance squared weighting for 24-hour storm totals near North Palm Beach, FL for January 2, 1999. As evidenced by Figure 1, the inverse distance squared weighting technique provides contours that are strongly circular in nature, particularly in the immediate vicinity of local maxima and minima.

Another procedure used for grid-based rainfall estimation is Kriging. (Kitanidis, 1997) Kriging uses the spatial correlation properties of the rain gage data field to produce weighted estimates of rainfall at each grid point. Kriging produces contours that are somewhat less artificial looking that the inverse distance squared methods, which is one of the reasons Kriging is a popular tool in the field of geostatistics. Figure 2 shows rainfall contours derived from Kriging using the same rain gage data presented in Figure 1.

One interpretive feature that's apparent in both Figures 1 and 2 is that these representations of areal rainfall imply that the highest rainfall amounts always fall at gage locations. Given typical rain gage network densities, the highest rainfall amount always falling on a gage does not seem particularly realistic. Yet that's what the rainfall maps developed from traditional techniques imply.

Also note the generally smooth contours and gradients in both Figures 1 and 2. The figures imply a smoothly varying rainfall data field, implying a highly consistent and predictable inter-gage rainfall variation.

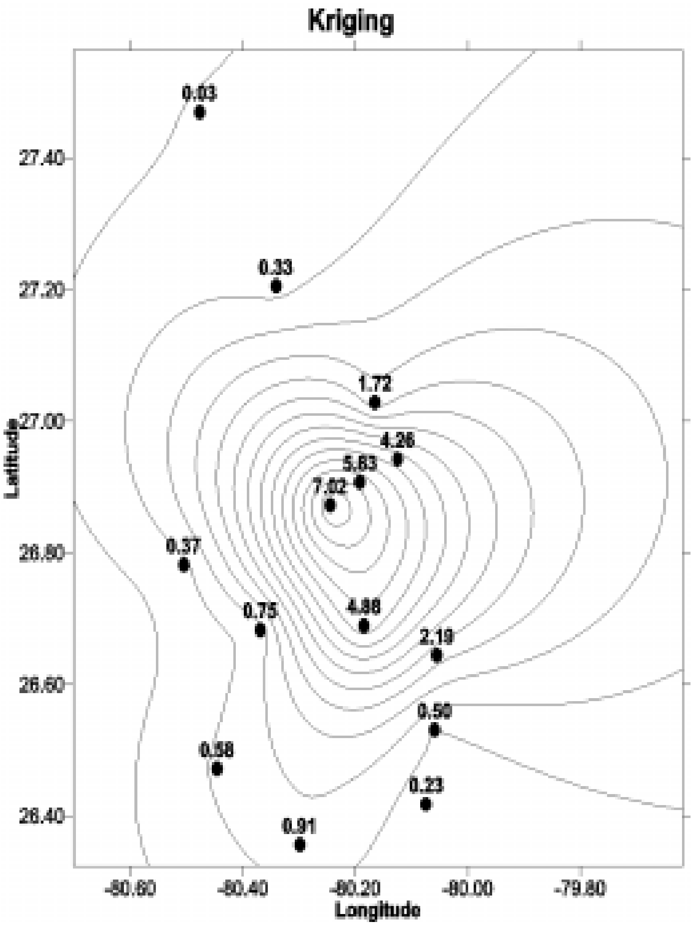

Figure 2: Rainfall contours derived from Kriging
(Values are rain gage measurements in inches.)

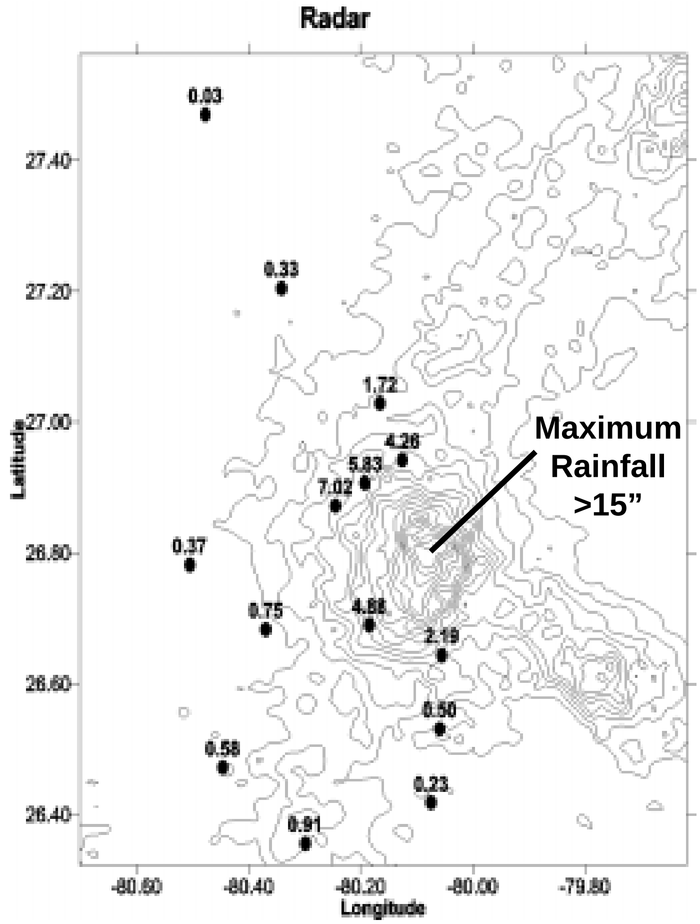

Figure 3: Radar derived rainfall contours
(Values are rain gage measurements in inches.)

Figure 3 shows rainfall contours derived from radar data with a 2-km x 2-km grid resolution. The radar-derived contours are very detailed, indicating a far more intricate storm structure than either Figure 1 or Figure 2 imply. Figures 1 and 2 imply that the highest rainfall occurred at the gage measuring 7.02 inches. Figure 3 shows that the maximum storm amounts occurred approximately 12 miles to the east of the peak rain gage reading. In fact, the radar-based analysis showed maximum storm totals exceeding 15 inches.

The general structure of the rainfall surface is also substantially different than in Figures 1 or 2. Figures 1 and 2 show rainfall features that are smoothly circular. The radar analysis showed rainfall contours elongated along a line from the southwest to northeast with a significant side lobe to the southeast of the storm center. Animations of the entire storm event show that during the early stages of the event, rain cells migrated from the southeast to the general location of the storm center, stalled, then exploded in intensity before drifting off to the northeast. After a brief lull, additional cells drifted in to the storm center, this time from the southwest, stalled, and exploded again before drifting off to the northeast. Thus, the shapes of the contours shown in Figure 3 are the remnants of the actual tracks of individual storm cells and indicate their general direction of motion during the event. None of this is indicated from the analysis of rain gage data alone as shown in Figures 1 and 2.

Figures 4-6 show a similar comparison for a much smaller and routine event occurring on January 27, 1999 in San Diego, CA. 3-D plotting was used in Figures 4-6 to enhance the visual interpretation of the derived rainfall surfaces. Figures 4-5 show rainfall contours derived from inverse distance squared weighting and Kriging respectively. Again, the rainfall features are depicted as generally smooth patterns with circular features at the highest rainfall amounts. Figure 6 shows the radar contours from the same event. Again much more detail is indicated by the radar-based contours. The radar-based contours are clearly more elongated in an east-west orientation, which matches the east-west movement of individual cells during the event. At least three distinct east-west cell tracks are shown in Figure 6. None of this detail is evident in the traditional rain gage analyses shown in Figures 4-5. Many of the surface gradients shown in Figures 4 and 5 are rotated nearly 90^{o} from the more realistic features shown in Figure 6.

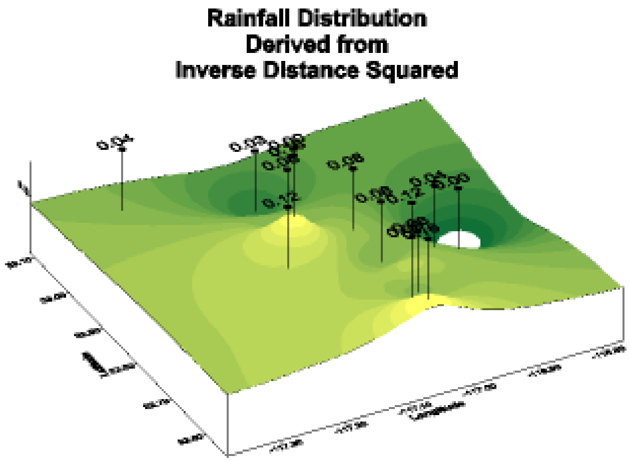

Figure 4: Rainfall contours derived from inverse distance squared weighting (Values are rain gage measurements in inches.)

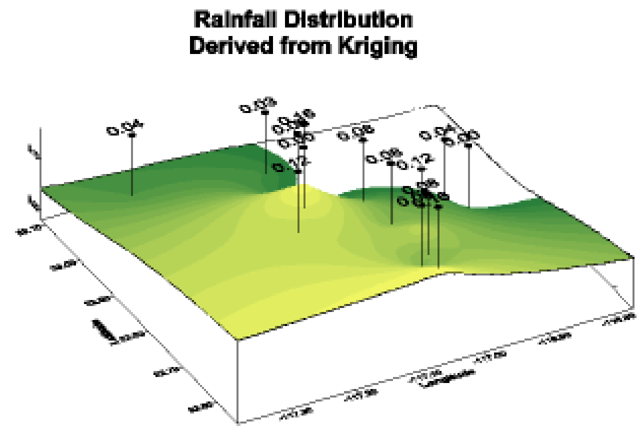

Figure 5: Rainfall contours derived using Kriging (Values are rain gage measurements in inches.)

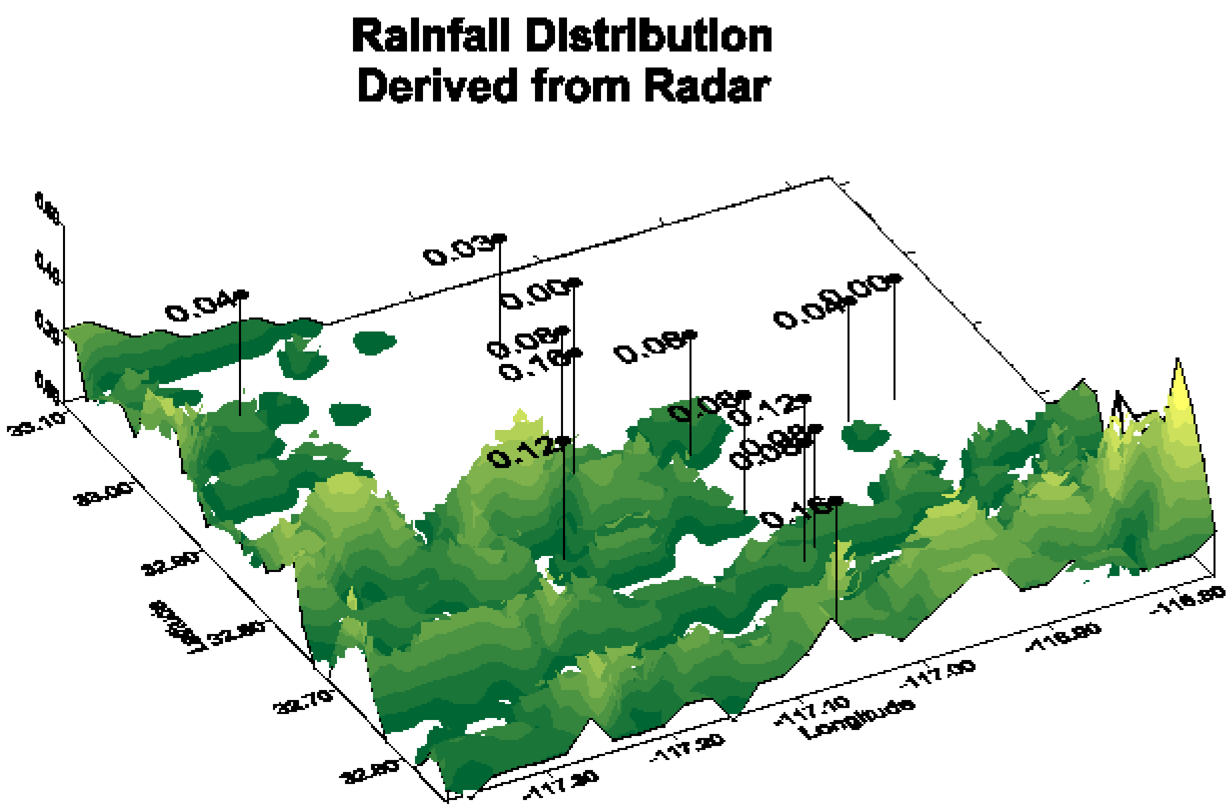

Figure 6: Rainfall contours derived from radar (Values are rain gage measurements in inches.)

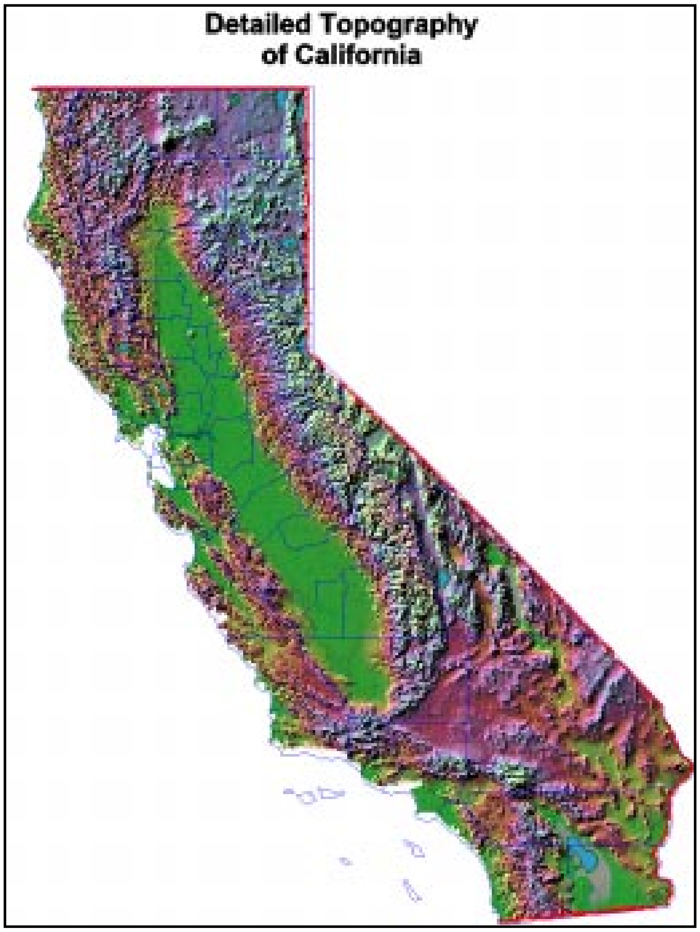

Figure 7: Detailed topography of California

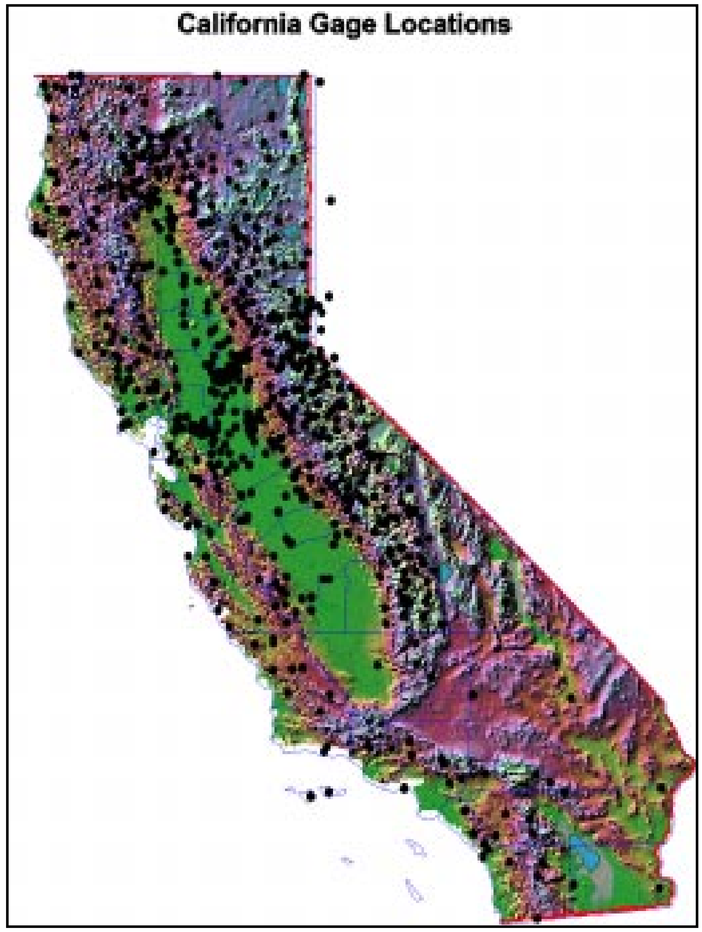

Figure 8: California gage locations

Topographic Analog

In recent years, the general public has grown accustomed to seeing highly detailed radar representations of rainfall during weathercasts on the nightly news. Intuitively the public seems to understand that these representations make sense, especially when individuals can simply look out their living room window to confirm the arrival of a heavy rain cell exactly as forecast by radar-tracking. However, when hydrologists get to work the next morning, the same traditional methods for spatial interpretation of rainfall that can dramatically misrepresent rainfall distribution are put to work again

One of the difficulties facing hydrologists is evaluating how well either rain gages or radar truly represent the actual distribution of rainfall. Part of the problem is that no one knows what the true rainfall patterns really are. Many investigators have shown that higher gage densities provide more detailed pictures of the spatial distribution of rainfall. However, we don't have a standard for comparison to measure how well the details are represented. In the absence of such a standard, hydrologists have grown comfortable using these traditional idealized representations of the spatial variation of rainfall.

To gain some measure of how well rain gage networks capture the true spatial distribution of rainfall, a topographic analog is used. Figure 7 shows a detailed representation of the topography of California. The topographic features of California are well known as they have been walked, driven, and flown over. These features have also been photographed and scientifically assessed by ground surveys, airborne reconnaissance, and satellite instrumentation. The location of nearly every rock in California has been identified. Thus, Figure 7 can be used a standard for California's topography with confidence.

Next, the question is asked: "What would a map of California look like if it were derived from a set of elevations sampled at the same rate that a state-wide network of instruments samples the hydrometeorology of the state?" Figure 8 shows the location of nearly 1000 river and rainfall monitoring stations obtained from the **C**alifornia Department of Water Resources **D**ata **E**xchange **C**omputer (CDEC). Elevations for each instrument were obtained and contours were derived using the

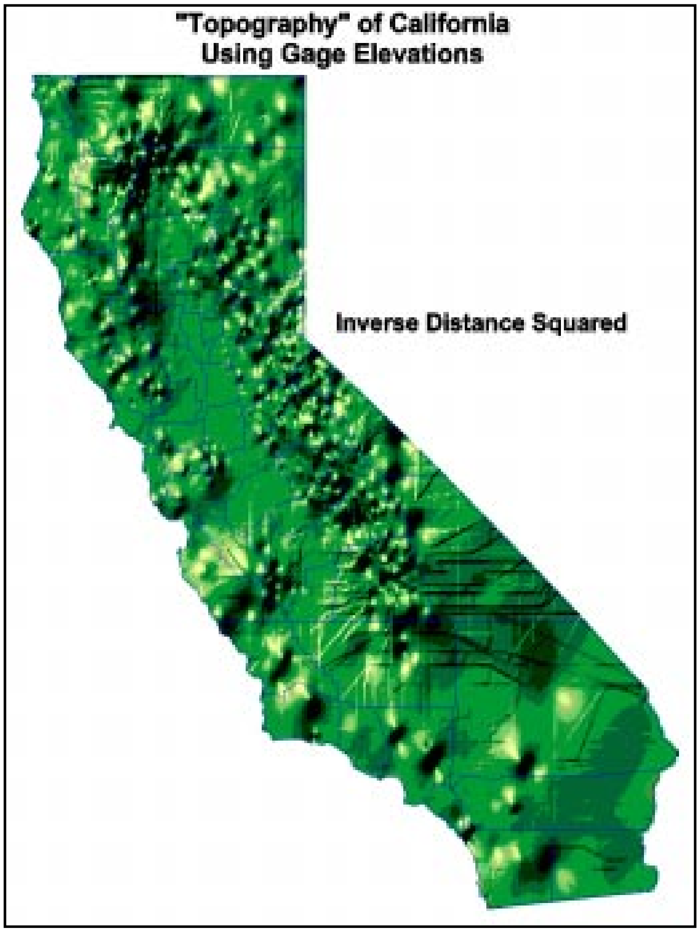

Figure 9: Topography of California derived inverse distance squared weighting

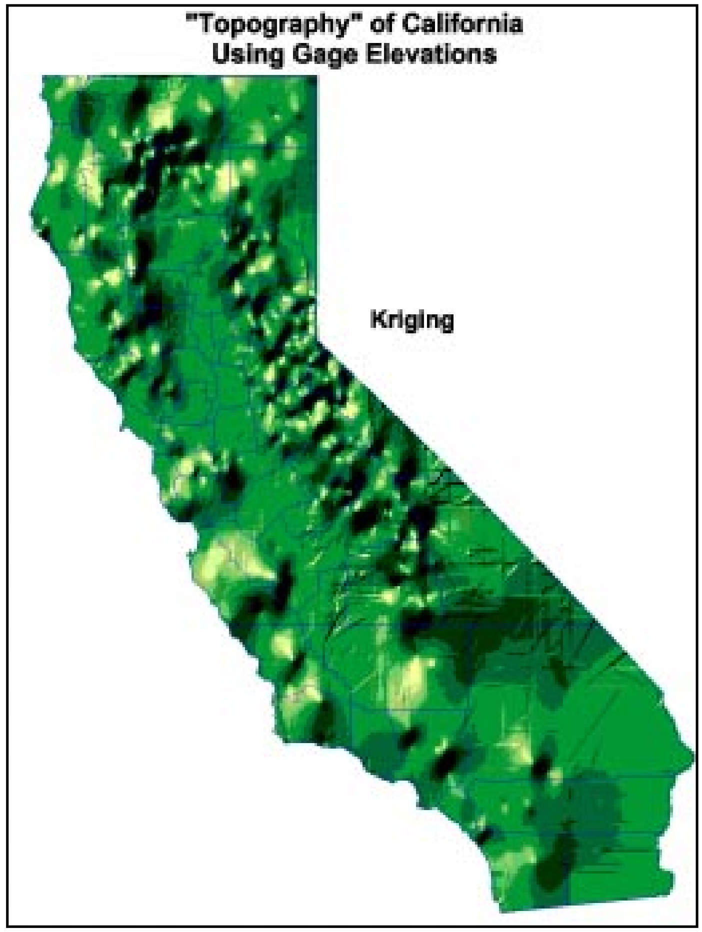

Figure 10: Topography of California derived from Kriging

same techniques used in Figures 1-2 and Figures 4-5. Figure 9 shows the *map* in shaded relief derived from the instrument elevations using inverse distance squared weighting. Figure 10 shows the shaded relief *map* derived using the Kriging technique.

Figures 9-10 both capture the largest scale features of California, namely the Sierra-Nevada Mountains along the eastern border and the large central valley. The coastal range of mountains is suggested but not well defined. Beyond that, most of the other details are clearly wrong. Large gaps in the coastal range of mountains are shown where none exist in reality. Sierra-Nevada mountain valleys are indicated as nearly county wide where as most of the major mountain valleys are actually just a few miles across.

Figure 9, derived from inverse distance squared weighting, shows the characteristic circular contours around local maxima and local minima. Kriging (Figure 10) helps depict a more natural looking topography but the local details are far from what is known to be true as shown in Figure 8.

The impact of sampling density on derived maps of complex natural phenomena is shown clearly by Figures 7-10. If it is assumed that the actual rainfall topology in California is at least as varied as the California landform topology, then the impact of rainfall sampling density on the interpreted rainfall surface should be similar. The gross trends might be defined correctly but local details are quite likely wrong. With this in mind, it's not so surprising that high-resolution radar-rainfall estimates present a much different picture of rainfall distribution than rainfall surfaces derived from traditional methods.

Implications

The implications that highly resolved rainfall surfaces have on hydrologic applications are wide ranging. For example, a prominent direction for hydrologic model development today is the integration of Geographical Information System (GIS) technology. Models such as the latest versions of HEC-HMS (COE, 1998) and WMS (Noman and Nelson, 1999) use GIS-based approaches to give hydrologists the ability to build watershed models with nearly limitless detail. Use of traditional rain gage technologies to build rainfall surfaces for input to these models invariably puts the wrong volume of rainfall at the wrong place at the wrong time, causing inconsistent model results. However, radar-based technologies offer hydrologists the capacity to more equitably match the rainfall resolution with the watershed modeling resolution.

Hydrologic standards are also potentially impacted by the new knowledge gained from high-resolution data sets. Local design regulations (e.g. Riverside County, 1978) often specify standard design storms that have defined shapes and orientations. These design storms are invariably derived from historical rain gage data. As the earlier discussions suggest, storm shape characteristics derived from point estimates are potentially suspect. It's possible that existing design storm shapes and orientations are substantially different that actual local storm topographies.

As the historical archive of radar expands, it will be feasible to derive historical frequency distributions of storm size, shape, orientation, tracks, genesis (locations of storm origin and termination), and storm duration. Design storms are often contrived to contain volume and intensity elements that span a variety of storm types. With historical archives of detailed spatial information, it will be possible to derive more realistic and more locally appropriate specifications for design storms.

Summary

Traditional rainfall analyses for hydrologic modeling use spatial representations of rainfall derived from rain gage observations at a series of points. These gage-derived spatial representations of rainfall are computed using any number of techniques including inverse-distance squared weighting and more advanced methods such as Kriging. None of these techniques have any relationship with the real world or provide any information about the true spatial distribution of rainfall. Radar, on the other hand, offers a significant analytical improvement for rainfall analysis by providing direct data more representative of the true spatial distribution of rainfall. The differences between the spatial distributions derived from radar and those derived from rain gages are often striking and dramatic.

Two case examples, one for North Palm Beach, FL and one for San Diego, CA, were presented. Rainfall topologies were derived using inverse distance squared weighting, Kriging, and radar methods. Inverse distance squared weighting and Kriging produced rainfall surfaces that were highly smoothed with dominant circular features in the vicinity of local maxima and minima when compared to surfaces produced high resolution radar data. Radar-derived contours clearly showed contours oriented along the principal tracks of individual rainfall cells.

An additional example was presented for topographic maps of California derived from elevations sampled at the same rate as California's CDEC gages sample the hydrometeorology of California. The resulting maps identified gross large-scale features of California's well-defined topography but most of the details were wrong. If California's rainfall is assumed to be at least as varied as California's topography, it is suggested that rainfall maps derived from the same point estimates might be similarly misrepresented.

The implications of these findings may have significant implications for modeling and hydrologic standards. The growing archive of radar-rainfall estimates will undoubtedly provide a rich resource for investigators and may challenge current assumptions regarding the spatial distribution of rainfall.

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